Università di Pisa

Scuola di Dottorato "Leonardo da Vinci"

PhD Programme in
Mechanical Engineering

PhD Dissertation

Prototyping for Research and Industry

Ing. Jacopo Tilli

XXVII Ciclo di Dottorato
Marzo 2015

Università di Pisa
Scuola di Dottorato “Leonardo da Vinci”

PhD Programme in
Mechanical Engineering

PhD Dissertation

Prototyping for Research and Industry.

Author:

Ing. Jacopo Tilli . . . .

Tutors:

Prof. Ing. Sandro Barone . . . .

Prof. Ing. Gualtiero Fantoni . . . .

Dott. Ing. Armando V. Razionale . . . .

XXVII Ciclo di Dottorato
Marzo 2015

a chi c'è sempre stato…

Ringraziamenti

Non voglio fare i soliti ringraziamenti, voglio evitare di elencare nomi. Sono certo che dimenticherei qualcuno. Ciò che voglio fare è ringraziare *te* che stai leggendo, perché se sei arrivato a leggere questa pagina significa che speravi che il tuo nome fosse nell'elenco che non ho scritto. Per sperare ciò vuol dire che abbiamo condiviso una parte di vita insieme, condiviso magari gioie, momenti difficili, momenti belli e chi più ne ha più ne metta. Le persone che voglio ringraziare sono quelle con cui ho condiviso la mia vita o parte di essa. Quindi ti ringrazio e dedico questo nuovo traguardo a te, indipendentemente che tu sia parente, amico, collega, professore. Grazie di cuore per esserci stato e spero tu continui ad esserci in futuro.

D'altra parte ci sono tre persone che voglio distinguere dagli altri, perché senza di loro non sarei quello che sono adesso. Grazie *Babbo*, *Mamma* e *Vittoria*. Se ho raggiunto questo traguardo è principalmente merito vostro.

Acknowledgments

I don't want to do the usual acknowledgments, I want to avoid listing names. I am sure that I would forget to thank somebody. What I want to do is to thank *you* who are reading, because if you are reading this page, it means that you hoped that your name was in the list that I have not written. To hope that, it means that we shared a part of life together, maybe shared joys, hard times, good times and so on and so forth. I want to thank the people who are the ones with whom I shared my life or part of it. So I thank you and I dedicate this milestone to you, regardless of whether you are, a relative, a friend, a colleague, a professor. Thanks for being there when I needed help and I hope that we may continue to be together in the future.

On the other hand there are three people who I want to distinguish from the others, because without them I wouldn't be who I am now. Thanks *Dad*, *Mom* and *Vittoria*. If I've reached this milestone it is mainly thanks to you.

Sommario

In questa tesi si vogliono presentare alcune delle attività svolte durante il periodo di Dottorato svolto presso la Scuola di Dottorato *"L. da Vinci"* nel periodo che va dal Gennaio 2012 a Dicembre 2014.

Le attività si sono svolte nei settori della robotica e dell'ingegneria meccanica in generale, ed il principale filo conduttore è stata l'attività di *prototipazione*, nonché l'attività di progettazione concettuale nelle sue diverse fasi, dalla generazione dell'idea, alla realizzazione e test dei prototipi.

La fase di *progettazione concettuale* è di fondamentale importanza per strutturare il processo di generazione di nuove idee. Talvolta è un processo che viene svolto in maniera inconscia da parte dell'inventore. Fornendo uno strumento che permetta di guidarlo nelle varie fasi della generazione dell'idea può portare a dei vantaggi che permettono di esplorare settori da cui trarre ispirazione, che non sarebbero altrimenti presi in considerazione da parte dell'inventore.

Un aspetto di fondamentale importanza nello sviluppo di nuovi prototipi è un processo che si contrappone alla fase precedente. Inizialmente la progettazione concettuale tende a fornire strumenti per generare il maggior numero di idee possibili, ma ad un certo punto si ha la necessità di selezionare un numero limitato di casi da approfondire. Tramite la fase di selezione, che si può strutturare su livelli più o meno articolati e più o meno qualitativi/quantitativi, l'inventore tende ad individuare, caso per caso, quali sono le idee su cui valga la pena investire tempo e risorse, prima di passare alle fasi successive.

La *prototipazione*, nonché la sua fase precedente, ormai comunemente denominata *pretotipazione*, sono invece tappe obbligatorie per chi voglia sviluppare una qualsiasi nuova idea, sia essa un prodotto o un servizio. Dall'analisi del pretotipo prima, e del prototipo poi, può dipendere il successo del prodotto o servizio finale, dal momento che permette di evidenziare limiti e possibili migliorie da apportare prima di passare alla fase realizzativa finale.

Abstract

In this thesis we want to present some of the activities carried out during the PhD studies held at the PhD School *"L. da Vinci"* in the period from January 2012 to December 2014.

The activities were held in the fields of robotics and mechanical engineering, and the main theme was the *prototyping* of new concepts, as well as the activity of conceptual design in its different phases, from generation of the idea, to the realization and testing of prototypes.

The conceptual design phase is of fundamental importance to structure the process of generation of new ideas. Sometimes it is a process that is carried out unconsciously by the inventor. Providing a tool that allows to guide him in the various stages of idea generation can lead to advantages that let the inventor to explore areas from which take inspiration, which otherwise would not have been taken into account.

An aspect of fundamental importance in the development of new prototypes is a process that goes in the opposite direction of the idea generation phase. Initially the conceptual design tends to provide tools to generate as many ideas as possible, but at some point there is the need to select a limited number of cases to investigate. Through the selection phase, which can be structured at levels more or less structured, and more or less qualitative/quantitative, the inventor tends to identify, case by case, which are the ideas in which is worth investing time and resources, before moving to the following stages.

Prototyping, as well as its previous phase, now commonly called pretotyping, are mandatory steps for those who want to develop any new idea. The success of the final product or service may depend from the analysis of the pretotype first, and of the prototype later, since it allows to detect limits and possible improvements of the concept before moving to the final implementation phase.

Contents

Chapter 1

Introduction

The present work is the result of three years of PhD studies, of some research projects (RobLog, NineSigma), of industrial activities (grippers for leather handling, automated systems for biomedical industry) and of academical experiences carried out in foreign research institutes and universities (BIBA and University of Texas at Austin). All the activities listed above merged into this thesis where the main topic is the prototyping activity for research and industry.

The initial part of the thesis was carried out in the PhD programme in *Automation, Robotics and Bioengineering*, where the candidate focused mainly on problems concerning the creation of concepts of grippers for the handling of heavy and deformable materials. One of the main activities during this part of the PhD studies was related to the RobLog project, and many grippers have been designed for the grasping of jute coffee sacks. Despite that, many other projects, still concerning the creation of concepts and prototypes were carried on, focusing both on industrial and academic solutions. During the last year, the studies switched to the PhD programme in *Mechanical Engineering*. In particular the activity was close to the *design and methods for industrial engineering* research field. Other research activities carried on during the last year, were concerning manufacturing methods and robotics.

Among the many projects followed both during the Automation, Robotics and Bioengineering and the Mechanical Engineering studies, only a selection is presented in this thesis, which are the ones concerning the prototyping activities for industry and research. Many other projects (e.g. Magna Closures, collaboration with the CIRP, abroad experiences etc.) are not presented here, even if they contributed significantly to the personal and professional growth of the candidate.

1.1 The core of the thesis

One of the main goals of the thesis is to establish a strong interaction between the academical field and industry, by creating and using methodologies, concepts and processes that can be used for both the sectors. In fact, it is opinion of the candidate, and hopefully of many of people he worked with, that in the most of the cases, research is meaningless if it cannot be transferred to real cases, that are usually represented by industry, and vice versa it is pointless to try to create something if it is not based on strong theoretical bases.

Prototyping is one of the most important steps in order to arrive to final products. Some of the steps analyzed in this thesis here are even not for the prototyping phase, but at a *pretotyping* [1] level. In fact, by reporting the definition, a prototype is *"the original or model on which something is based or formed, as the first working model of something to be manufactured on a large scale"*. Many activities studied are even preceding the manufacturing of a physical object, like the Design by Analogy that will be analyzed in Chapter 3, or some concept selection phases that are described in Chapter 4.

1.2 Structure of the thesis

In order to better contextualize the work, the phases that have been analyzed are the ones in dark blue in Figure 1.1, where the scheme illustrates the product design phases according to Ulrich [2].

The work has been divided into macro areas: the first one is an overview of the *Concept Design* phases, and is analyzed in Chapter 2. This part is an introduction that should help to better contextualize the importance of the work, and to understand which part of the prototyping phase are studied and analyzed.

Following the *Concept Design*, the study of the *Design by Analogy* is discussed in detail in Chapter 3. This phase is at a conceptual level, concerning the creation of new concepts, the analysis of unexplored field for invention, the overcome of fixation during the conceptual design phase.

In Chapter 4, methods for helping in the *selection of concepts* are studied, in order to support the choice of the most promising concepts to be developed. The choice and selection of concepts, with some case studies for gripper selection.

Some practical cases are illustrated in Chapter 5, where the methodologies treated in the first Chapters have been implemented, but at the same time some limitations and drawbacks of the prototyping phases are put in evidence.

Chapter 6 propose some solutions to overcome the limitations of prototyping techniques, particularly related to mechanical properties of rapid manufactured components, processes used for manufacturing pretotypes and prototypes and for the customization process of large scale production.

Some parts of the thesis are partially based on previous works and papers of the candidate and his research group, while some other parts have been used for the submission of papers that are, at the present moment, under review. In particular the part concerning the Design by Analogy (Chapter 3) is based on the paper *Concept design of new grippers using abstraction and analogy* [3]. Chapter 4 presents some works of the author and of his research group presented in [4] and [5].

Chapter 6 is based on many works and papers: Section 6.3 concerns the activities done during the period spent at the University of Texas at Austin, and a paper related to this activity has been submitted to the AITeM conference (*Improving mechanical properties of laser sintered Nylon-12* [6]). Section 6.4 is based on three papers of the author submitted to the ICIDM conference [7,8] and SFF Symposium [9]. Finally, Section 6.5 is based on a paper submitted to the ASME conference, titled *A novel methodology for the creation of customized eruption guidance appliances* [10].

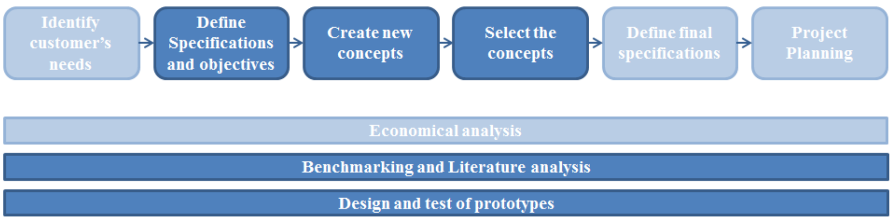


Figure 1.1: The product design flowchart. The phases analyzed in the thesis are in dark blue.

Chapter 2

Overview

Every activity where the creation of a new product is intended as the main goal of the project requires as initial step the planning of the activities. According to Ulrich [2], the concept development phase covers four macro-areas: (i) Marketing, (ii) Design, (iii) Manufacturing and (iv) Other functions (finance, management...). In this work, marketing and economical analyses will not taken into account, but the thesis will focus on the *concept development phase*, analyzing especially the design and manufacturing aspects.

The following Sections introduce the themes that will be analyzed in the following Chapters, giving an overview of which is the main topic of each Section.

2.1 Concept design phase

The conceptual design phase, as suggested by Ulrich [2], can be divided in the following seven subsequential steps: (i) identify the customer's needs, (ii) define the objective, (iii) create new concepts, (iv) select the concepts, (v) evaluate the concepts, (vi) define the final specifications and (vii) plan the project.

Simultaneously to the substeps listed above, other activities have to be carried on, concerning mainly the following points:

- economical analysis
- study of concurrent products and benchmarking (literature study)
- prototyping and testing of the concepts

The steps that have been analyzed in the present work are the ones that go from the definition of the objectives, even if the most of the work started from the creation of new concepts, to the evaluation of the concepts. Moreover, other activities presented in this work concern the study of literature and the prototyping and testing of new concepts.

2.2 State of the art and literature analysis

The development of new concepts cannot disregard a deep analysis of similar products already available both on the market or already studied and presented in the literature. In order to avoid fixation, it is opportune not to analyze the concepts already present in Academia or Industry before a brain-storming phase. By inverting the two phases, it could happen that the inventor focuses too much on already existing concepts, trying to emulate or to modify them (this aspect will be deeply analyzed in Chapter 3), thus limiting the exploitation of unexplored fields for the invention.

On the other hand, once ideas for new concepts have been generated, it is necessary to check if what came out from the brain-storming has already been conceived. If the idea is new, it is still possible to take advantage of similar concepts already generated, in order to understand which are the main advantages and the main drawbacks.

2.3 Design of new concepts

The concept can be presented as a draft or sketch, or even only a written description of the product. Sometimes this is not enough for evaluating the mechanical properties of the solution (*work-alike*), or to have an idea of how the final product would *look alike*. *T*he purpose of the testing of concepts is to estimate the reaction of potential customers to a product concept before investing other resources in its development. Moreover, in the industrial field, the concept testing can be used to identify the segment of the market and opportunities for improvement.

2.4 Selection process

Once concepts have been generated, the subsequent step is to analyze them and to identify the most promising ones. In order to do the selection, some supporting instrument and methods are available, that structure in a more formal way the selection process. They can be more qualitative or quantitative, with a higher quantity of information or with a schematic approach, but the goal is the same: give some criteria for the selection of the concepts to analyze more in detail and to develop more. This topic is analyzed in detail in Chapter 4.

2.5 Manufacturing and testing of the prototypes

Once the prototypes to be manufactured have been selected, there are many different ways for creating the concepts. Among the traditional techniques, there are the traditional operation performable on the machines available in a common workshop (e.g. drilling, milling, turning) and their functioning is well known from academic literature [11, 12]. Moreover, in the last years, the importance of Rapid Prototyping techniques in the prototyping phase raised considerably. An overview of the state of the art of rapid prototyping can be found in many books [13] and research papers [14].

The testing of concepts is closely linked to the selection process , since both aim to reduce the number of concepts to be considered. Testing is a subsequential phase which aims at evaluating certain performances (e.g. dimensional, mechanical, functional) of the concepts, even though there is room left for improvements.

Chapter 3

Design by Analogy

This Chapter explores the possibility of creating new concepts using *analogy*, in order to expand the number of concepts that can be created. The purpose of this Chapter is to present and explain a six-steps method based on problem formulation, abstraction and Design by Analogy, whose goal is to structure the technique for generating new design solutions. The methodology proposed was then tested over the Design by Analogy of new grasping system for the RobLog Project, and some of the results are presented at the end of this Chapter.

3.1 Definition of Design by Analogy

Design by Analogy is a powerful technique for new design solutions. In the literature there are two possible approaches. The first one is more user friendly but is low structured. The other is more complex, which structures the problem better but is highly time-consuming. This Chapter presents a simple system for structuring the Design by Analogy method, which is based on the abstraction of the problem. The application of this system increases the design possibilities, and results can collected in a repository, whose order is based on functional logic. The proposed technique was tested on the conceptual phase in the design of novel grippers and in many other fields that will be presented in Chapter 5.

The Design by Analogy process can be extended to many different fields. The method can be used as a creativity support during the design phase, also creating repositories that can be enlarged and reused for different applications. In this case the methodology was applied for the development of innovative grippers for the RobLog Project [15], that will be treated more in detail in Section 5.1.

During the conceptual design phase, often the designer try to generate different alternatives and to explore divergent design solutions. In this phase, several methodologies are often used to abstract the problem and to formulate innovative ideas and products. A powerful technique for exploring new concepts is Design by Analogy. It allows the designers to take inspiration from the functioning of different objects and living beings. In the literature the main approaches are located between the two following cases:

1. The first one groups user friendly but low structured approaches. They are based on lexical analysis (synonyms, antonyms, hyperonims etc..) and sometimes are enhanced by software or databases, such as in [16, 17]. Databases are generally used as a further source of inspiration for the designer. Generally they are very simple tools, easy to use, but they provide only general ideas and not detailed solutions.

2. The second one collects more complex but more structured approaches. They help the designers in structuring the problem in a better way through several steps, but they are highly time-consuming. These methods can be based on functional approaches [18] or on the TRIZ theory [19]. The long learning time represents the main drawback of such methods.

The present work would like to fill the gap by presenting (i) a simplification for structuring and abstracting the problem and (ii) a structured way for systematizing heuristic approaches. The method has not to be considered as a novel method invented by the candidate and his research group, but instead a reinterpretation of methods already known and applied both for research and industry. The first step of the proposed approach starts from the abstraction of the problem, as the TRIZ theory suggests [19]. Then, following a functional perspective (similar to Nagel et al. [20]), many similar products, systems or living beings can be identified in a structured way. The identified products, systems or living beings are then clusterized in a database according to a functional logic. Then they become a new source of inspiration for the designer. As we will detail in the following paragraphs, the presented methodology benefits from some of the fundamental steps of the structured methods, but it remains simple to learn and to be used.

3.2 State of the art of Design by Analogy

Design by Analogy is a useful methodology often adopted by professional designers, both at academic and industrial level. Sometimes the analogy technique is adopted considering only elements belonging to the same domain as the product under study (close-domain analogies). However, less often, different fields are also investigated (cross domain analogies) to expand design possibilities [21, 22]. The latter approach is extremely useful, especially during the starting phase of the conceptual design, because it allows designers to discover new ideas for the creation of novel products. Nevertheless, while Design by Analogy is often performed without a formalized methodology in industry, different design theories and problem solving methods based on Design by Analogy can be found in literature. For example, Synectics is a structured approach to the creative problem solving activity, based on analogical thinking. It identifies four different mechanisms which stimulates the creative thinking: direct analogy, personal analogy, symbolic and fantasy analogy. A more structured method is the "theory of inventive problem solving" (TRIZ) [19]. The approach followed in TRIZ considers initially the abstraction of the problem, followed by the identification of the contradictions, then the research of a solution by analogy within the 40 inventive principles. Such principles have been extracted from a corpus of 2 million patents [19] and have been demonstrated to be stable with the passing of time [23]. Even if the inventive principles allow the designer to find the solutions to the contradictions, the methodology is complex and it has a long learning curve.

Mc Adams et al. [18] provided a measure of the similarity of the products through the concept of functions and flows. Starting from the users' needs, the functions that the product has to carry on are identified. After that, through an appropriate database, those products sharing a functional similarity are chosen for a cross over. Mc Adams explored only the electro-mechanical devices domain, neglecting other possible sources of inspiration.

Similarly, the method developed by Fantoni et al. [16] focused on the concept of function. They described a technique based on functional analysis and on the analysis of functional synonyms and antonyms for the development of new ideas.

Another method which supports the design activity, stimulating creativity and reasoning by analogy at the same time, is the wordTree design-by-analogy method [17]. This method systematically guides the designers in the identification of analogies and analogous domains thanks to the investigation of the lexical relationships among words (hyperonims, meronims, synonyms, etc.). Conversely Bonaccorsi et al. [24] developed a wide and interconnected functional dictionary, where vertical and horizontal relationships are mapped through synonyms and antonyms. Such extended dictionary offers the possibility of designing alternative solutions by using functional similarities or variants but it is limited to functional verbs and flows.

These latter two techniques are useful in giving inspiration to the designer, but they are not structured. A huge source of inspiration for new solutions comes from nature. Several works deal with the systematic transfer of biological knowledge into the engineering domain. Indeed, biomimetic design "offers enormous potential for inspiring new capabilities for exciting future technologies" [25]. Several researchers have used biological analogies for the generation of concepts [26–28].

In particular, through the concept of function, some of these works identify the biological elements to develop bio-inspired concepts. For example Shu et al. [29] combined functional modeling and biomimetic design, by incorporating biological phenomena into a function based design repository. Similarly, Nagel et al. [20] presented a general method for the functional representation of biological systems through systematic design techniques.

The systematic search for inspiration in the biological field has pushed the research towards the development of databases and softwares. For instance Chakrabarti [30] created a software called IDEA-INSPIRE, which uses a database of natural and artificial systems classified by a verb-noun-adjective triplet. Vincent and Mann [23] constructed a condensed TRIZ contradiction matrix (bio-triz matrix), that enables designer to abstract useful design information from biological systems. Although the biomimicry allows designers to identify really innovative design solutions, this technique focuses only on living organisms domain. Robotic research has always shown a deep interest in bio-inspired grasping principles [31]: one of the most interesting research activities is the gecko climbing system studied by Cutkosky's team. The climbing robot they developed is based on Van der Waals' forces and hierarchical structures [32], while Matope et al. [33] transferred the concept to a microgripper.

3.3 The methodology

In order to overcome fixation and to explore also lateral ideas, we approached the problem of designing new products by using a crossover strategy (i.e. by using Design by Analogy). The idea behind is to find, in common days life, a source of novel ideas inspired by the objects used to carry on a desired function (hereafter named inspiring elements). A large database of these objects can be created in order to capture their behaviors, which concur to provide the researched functions. Each one of them can be described in functional terms (e.g. using the dictionary in [34] and [24]) to enhance their retrieval. Unfortunately, even if powerful, Design by Analogy is a very low structured technique. Therefore, instead of starting with the research of analogies, we propose a six-steps divided in the following six steps:

1) ***Problem and requirement definition*** – The designer has to define the requirements and the constraints of the problem;

2) ***Abstraction of the Problem*** – The main desired function is identified. This is the base of the following design by Analogy;

3) ***Collection and clusterization of the inspiring elements*** – Working by analogy, the designer collects and clusterizes into a repository the elements that carry on the desired function;

4) ***Functional and Statistical analysis*** – The main function can be decomposed into sub-functions. A statistical analysis of the sub-functions used in the inspiring elements and in the similar products is performed. The comparison of the two statistics allows the designer to highlight the unexplored areas;

5) ***Design and new concepts*** – All the elements in the repository are based on a specific physical effects that can be used as a source of inspiration for new concepts;

6) ***Concept selection*** – The starting requirements are used to select the product concept.

3.3.1 How to apply the method to the design of new grippers

Even if the method can be easily understood, we would like to apply it to a real case in order to better illustrate the procedure through its steps. The application is the design of new grippers. By applying the Design by Analogy heuristic at the problem level without using a structured method, we can find interesting sources of ideas in new industrial grippers or in robotic hands, but such an analysis looks much more like benchmarking than an inventive activity (Figure 3.1 left arrow). In fact, both the number and the diversity of the found analogies are reduced if compared to the more systematic analysis proposed here. For comparison the reader can refer to the seminal work of Novitskaya [35], where she attempts to demonstrate the similarity between grippers and some structures belonging to absolutely different technical systems. Even if the idea is correctly expressed and the case study describes a gripping device, the approach is far from being systematic.

By abstracting (Figure 3.1 vertical arrow), and so generalizing the problem, the field of research can be enlarged. Abstraction plays a major role in the early stages of engineering design and it is a valuable tool during the conceptual design phase [36]. It is also the first key step in TRIZ algorithm [19] while it also plays a relevant role in functional decomposition [26, 27, 37].

The abstracted problem can be described as follows: "to find a system that, when acting on the object (i), reduces the degrees of freedom of an object with respect to the system itself". The research of solutions was carried out through several brainstorming sessions and through several contributions developed independently by the researchers. The goal was to identify the living beings and non living things that, through different mechanisms, perform the researched functions (Figure 2 right arrow and clusters).

Working by analogy the following areas were explored:

biology and botany (in a sort of biomimetic approach), varying from insects legs to animal trunks and tongues, investigating animal climbing systems or insects' reproductive apparatuses or even plant glues or seeds shapes;

appliances and tools , varying from snap-fits to locks, investigating gym devices as climbing cams or parachutes or even common day life tools as umbrellas and epilators;

weapons as harpoons , varying from hook to hand harpoon, investigating simple or expanding bullet or even arrow or broadhead arrow;

clothes and accessories , varying from belts to laces, investigating hairclip or nose-piercing or even zip or a button in a buttonhole.

3.3.2 Functional decomposition of systems that grasp objects

Whichever system is selected, standard gripper and robot hand, or novel grasping device, it has been analyzed in a formal way. First of all, for each gripper, hand, device or animal, a suitable reference was identified to clarify the functioning of the system of interest. This is important in particular to understand

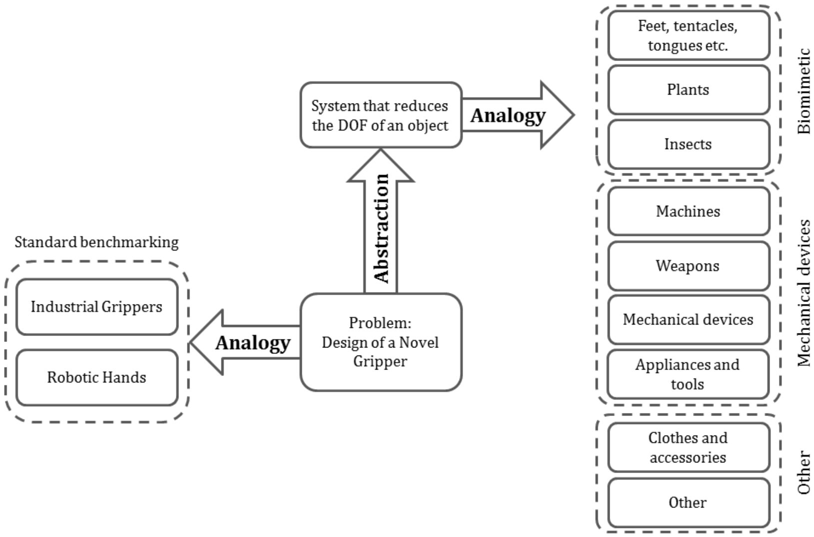


Figure 3.1: Sources of inspiration for Design by Analogy.

the correct behaviors, especially for biological systems, with which engineers have no familiarity. To make the analysis as rigorous as possible, a step-by-step top-down procedure based on Functional Analysis (FA) has been chosen. As seen in session two, different works resort to the concept of function, since it provides an abstract representation of the product. In engineering design, the definition or the comprehension of a system in terms of function, is a fundamental aspect [38–40] that helps designers in conceptualizing and evolving the design. Functional Analysis (FA) helps the study of complex systems by breaking them down into simpler sub-functions.

During the 60s in Germany, a catalogues of effects, principles and solutions was developed to provide abstract representations of the functioning of objects, in order to help the designer in choosing the best solution [26, 34].

Later several attempts to standardize the functional lexicon emerged in the literature [41–43]. Even more structured are the proposals by Little et al. [44], who introduced the notion of functional basis, and Stone and Wood [45] that continued on the same track combining the classification of functions in classes with the structure of a basis. These efforts of synthesis culminated in the Reconciled Functional Base proposed by Hirtz et al. [34], who suggested a hierarchy of functions organized in three levels. Such taxonomy has been adopted in the present work.

Therefore the decomposition moved towards the identification of the phases [46] occurring during the utilization of the gripper, the actions performed by the animal or the product's phases of use. The identification of the phases makes it easier to create a detailed functional description. Then each phase was split into elementary functions and, to obtain homogeneous functional decompositions , phases were labeled by using the functional dictionary of Hirtz et al. [34]. Finally, each gripper was classified according to the physical effects involved during the functioning [47].

In particular, it is worth noting that the analysis of the elementary functions allows mapping both the main function and also those functions supporting the grasping. In order to reduce ambiguities, the handling based on grasping was split into standard phases and all the systems (included animals, devices etc.) were dealt according to such a set of phases.

In general parts grasping [48] consists of the following phases (shown in Figure3.2 in case of a mechanical two fingers gripper):

1. approaching the object: the gripper is open, and the robot system positions the gripper close to the object;

2. coming into contact: the gripper is actuated and its surface touches the object surface (in case of contactless handling the object is in the range of the force field generated by the gripper);

3. increasing the grasping force: the grasping force has to reach a value able to provide a stable grasping;

4. securing the object: the force stops increasing, when the object stops moving independently from the gripper;

5. lifting the object: the gripper and the object are joined and the object can be lifted (if the payload of both the robot and the gripper allows it);

6. releasing the object: at the macroscale, when the grasping force is removed, gravity helps to release the object. At the microscale the problem is more complex, therefore other releasing strategies has to be found [49];

7. monitoring the grasp: many different sensors (force and torque, stick-slip, contact sensors, etc.) are used to monitor the contact and the effectiveness of grasping.

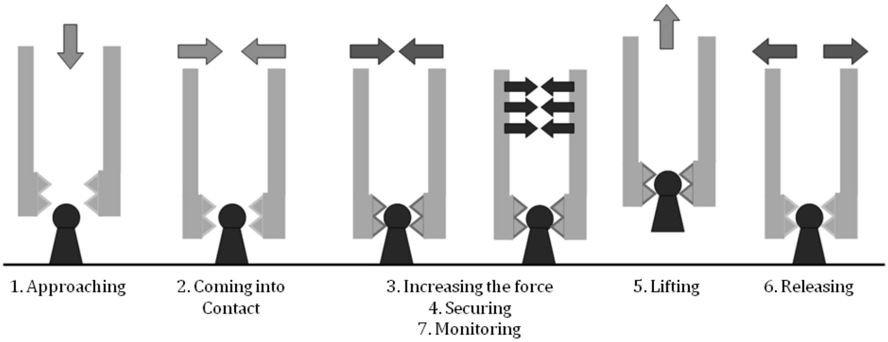


Figure 3.2: Standard phases sequences in assembly or goods handling.

Phases like number 1 and 5 are usually performed by a robot or other handling system, while phase number 7 can be done both locally, at the gripper level, or globally ,at robot or environment level (through fixed cameras).

3.4 Application of the method to the design of new grippers

Nowadays grippers are changing towards a more and more complex design to accomplish the most various tasks. Even if research is pushing toward this direction, simple high-efficiency grippers are still studied and produced for common industrial operations. Actually, high performances usually imply high costs, which are not possible in a competitive industrial scenario. Because of this fact high dexterous hands are mostly used in research activities or for particular manipulation cases, while simple and reliable grippers are intensively exploited in industry.

Figure 3.3 shows the space of automatic grasping devices. On the left side different industrial grippers are shown, while on the right one a few robot hands are presented. Examples of the two categories are vacuum cups, two finger mechanical jaw for the industrial grippers, and Vassura's hand or Waseda University Hands [31] for what concerns the robotic end-effector.

The most important features for industrial grippers are the force, generally higher than in robotic devices, and the structural stiffness, which influences the quality of grasping, positioning etc. [31]. Moreover the reduced number of degrees of freedom increases the reliability of the gripper and reduces its cost. The robot hands, compared to the industrial grippers, have an higher compliance and dexterity (mainly due to the increased number of DOFs) that allow the manipulation of objects in a human-like way.

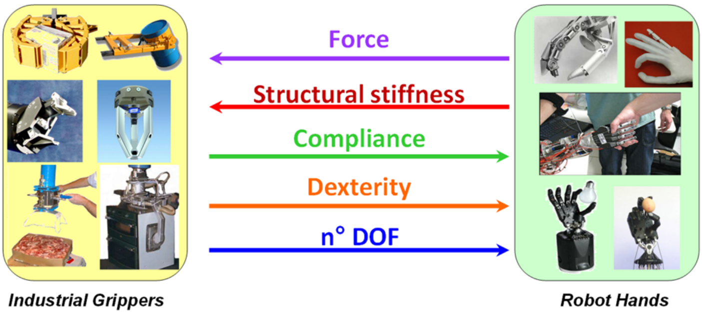


Figure 3.3: parameters and performance vary from industrial grippers to robot hands.

3.4.1 "Non conventional" grasping systems

The methodology presented was applied to create a database that supports the designer in inventing *non-conventional* new grippers during the conceptual phase. As we stated before, in order to overcome a rigid and convergent approach to the problem we decided to explore devices or living beings and non living systems that acts (also for short time periods) as grippers.

Definition of gripper
Grippers are defined as "a subsystems of handling mechanisms which provide temporary contact with the object to be grasped [...] and ensure the position and orientation when carrying and mating the object to the handling equipment[...]; the term "gripper" is also used in cases where no actual grasping, but rather holding of the object where the retention force can act on a point, line or surface [...]" [50].

Therefore it would be helpful to find other systems, that are not classified as grippers and match such a definition. Hence, a database made up of about 150 elements has been created [51]. This database contains the names of the "non conventional" grippers and the relative functional decompositions of the grasping phases. The entries of the database are classified according to (i) the grasping mechanism (e.g. adhesion, grasping, pinching or punching) and to (ii) the fields whose they belong to (e.g. biology, appliances and tools, clothes and accessories, weapons, etc.).

Examples of convergent suggestions in the database are seat belts, fish nets, mechanical devices; more divergent ideas are, for example, umbrellas, stents, car latches, etc. Moreover, even accidental and unwanted events as the nesting between springs or the tangling of trousers into a gear systems or in the bicycle chain can be useful in inspiring novel solutions for grasping.

Systems that grasp objects but are not considered grippers						
ADHESION						
Analogy	**Correspondent**	**Class**	**Coming into contact**	**Increasing the grasping force**	**...**	**Releasing**
glue	carnivorous plant, resin, honey	A	contact	increase P- deform – import- stay(little) – attach		move- deform- resist- separate- deteriorate- allow DOF (irreversible)
glue with volatile component		A	contact	increase P- deform – import- evaporate - stay(little) – attach		move- deform- resist- separate- deteriorate- allow DOF (irreversible)
tape	plaster	A	contact	increase P- deform – attach		move- deform- resist- separate- deteriorate- allow DOF (irreversible)
termhal glue		A	increase temperature - transform solid in liquid – contact	increase P - deform - import - stay - transform liquid in solid - attach		move- deform- resist- separate- deteriorate- allow DOF (irreversible)
sticky hands	anteater tongue, camaleonte, drosera and pignicula(carnivorous plant), cyber clean	A/B	contact	deform - increase surface - mate (fine) - attract- attach		move (peel)- deform- resist- separate- allow DOF
giant anteater tongue	hekidna	B	move into- deform spine- slip- contact	deform - increase surface - mate (fine) - attract- attach - move out - deform (spine)-resist-connect- store		move (peel)- deform- resist- separate- allow DOF
velcro		C	contact - couple - guide	move- nest - block movement (hold)		move - increase force- deform - resist- slip - deform back -- separate- allow DOF
spiral (severe nesting of springs)		A	position -contact-rotate- guide-translate	deform -block		move - increase force- deform - resist- slip - deform back -- separate- allow DOF
vacuum cup		A	contact	export air - decrease pressure -deform- connect		import air- increase pressure - allow DOF-separate

Figure 3.4: Screenshot of the database.

Figure 3.4 is a part of the database which shows elements satisfying the definition. For instance during the use of a parachute, it contains and constrains the air (it is a sort of temporary gripper for air). Another example is the brake that grasps the wheel, decreasing the vehicle velocity by friction. One more interesting object is the stent, that is inserted in the veins and arteries of the human body to counteract a localized flow constriction. Usually it is passed into the narrowed locations and then it is inflated. Thus the balloon pushes the metallic stent that crushes the fatty deposits, opening up the blood vessel and restoring the flow. Its functions of blocking the fat and holding the blood vessel in an open position satisfy the gripper definition. Some entries of the database show the same functional decomposition therefore they can be considered identical, even if they are structurally different. These elements are in the column called correspondents. Indeed, the same functional chains can be carried out through different elements and even different physical principles. For example a plug, a stent and a latch perform the same functions to block and to hold.

3.4.2 Occurrence analysis

Occurrence analysis for standard grippers For each grasping principle [52] one standard gripper was selected and analysed through functional analysis (Figure 3.5), since grippers exploiting the same grasping principle show almost the same behaviour. As a note, the functions related to the lifting and realising phases were skipped, since they are repetitive and mainly based on robot capabilities and gravity, respectively.

GRIPPER	FUNCTIONAL DECOMPOSITION
Two fingers grippers (for rigid objects) force closure	position, bring close, set d, contact, deform the object (micro), deform gripper, orient, align,shift, increase force, increase friction, block
Multifingers gripper (for flexible objects) form closure	bring close, contact, enter between sacks, deform the object (macro), lift the object, move (down) by g, deform the object (macro)
Pneumatic expansion gripper	import air, modify shape, increase volume, orient, align, shift (mate coarse), increase force, mate, increase friction, connect
Needle gripper	extract needle, contact, increase P, separate, guide, move, nest, block, connect
Vacuum gripper	contact, deform, mate, export air, decrease P, deform suction cup, deform object, mate, connect
Bernoulli gripper for light objects	position, bring close, import air, decrease P, lift, move, approach, push, decrease P, stabilize
Capillary gripper	import water, distribute, create depression, attract(capillary), connect
Liquid-solid transition gripper	export water, contact, decrease T, transform water, join
Magnetic gripper	create magnetic force, attract, hit, resist, connect, stop magnetic force, separate by g
Electrostatic gripper	supply voltage, create electrostatic force, attract, hit, resist, connect
Van der waals gripper	contact, create electrostatic force (multiples), attract, hit, resist, connect
UBH HAND	bring close, contact, deform(micro), orient, align, shift, increas (force), start lifting the object, increas friction, lift
Gripper with flexible arms	position, orient, align, bring close, mate, deform the object, increase force, increase friction, lift

Figure 3.5: Screenshot of the functional decomposition of the main grippers.

Such decompositions can be considered as the baseline of the frequency analysis. The most occurring functions have been plotted in the Pareto's histogram shown in Figure 3.6. As expected, the most repeated functional verbs are those related to the grasping and handling phases (to position, to bring close, to align, to connect, to mate, etc.). Some of them are peculiar to the grasping process, while others, such as to mate and to connect, show how grasping benefits from high coupling of gripper and object surfaces (often achieved through the deformability of the couple gripper and object).

Occurrence analysis for non conventional grasping systems Also for the non conventional grippers a frequency analysis has been performed, in order

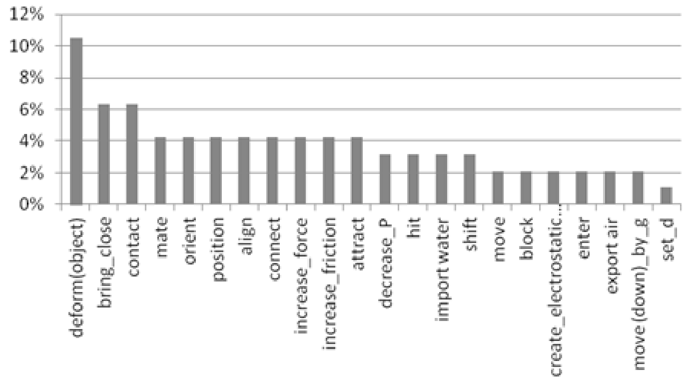


Figure 3.6: Pareto histogram of the most occurring functions.

to identify where interesting changes emerge from the comparison of the two groups (conventional vs non conventional). Figure 3.7 shows the results concerning the top 30 functions.

In the case shown in Figure 3.7 the function "to deform" is split into two parts: gripper deformation and object deformation. The sum of gripper deformation and mating is relevant and their synergy plays a key role (even more important than in conventional grippers). This is probably due to the presence of biological systems, where the coupling of grasping device and objects surface is necessary to increase reliability and to decrease the amount of energy requested for the grasping (that, for example, is the base of the climbing of geckos, tree-frogs, squirrels, insects, etc.).

The exploitation of a high coupling between gripper and object is, and probably will be even more in future, an interesting research area in robotic grasping. However its investigation is out of scope with respect to the aim of this work.

3.5 An industrial case study: Robotic unloading of goods from containers

Automation of mass goods has become more and more important for logistic companies. Reasons rely both on process cost and workers' health issues. Especially, the handling of heavy and deformable materials is one of the most challenging problems for this sector. The EU has approved the RobLog project whose main goal is the automatic unload of containers. The method presented

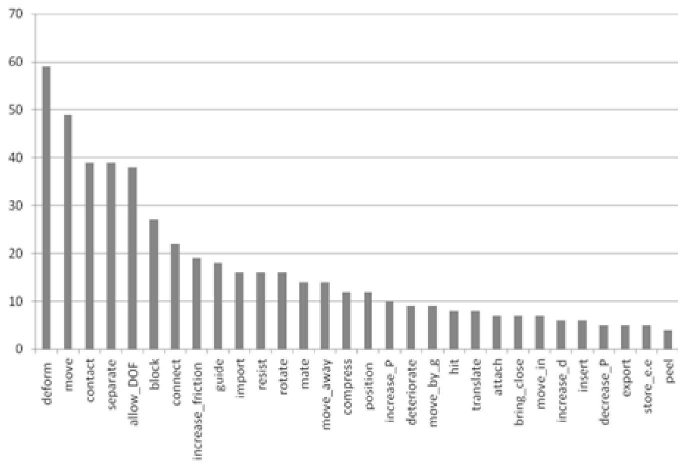


Figure 3.7: Pareto histogram of most occurring functions in non conventional grippers.

above was applied to the development of the grasping part of the robot. Because of the wide variety of goods to be handled, one of the main goals is to set the specifications, both of the goods to be handled and of the grasping system. For the specific case of study, the gripper has to grasp jute coffee-sacks, whose requirements are:

R1 weight: 25 kg – 75 kg;

R2 maximum dimensions [mm]: 600x300x900;

R3 material of the sack: jute (porous);

R4 contents of the sack: coffee beans (deformable);

R5 maximum damage admissible: 200 mm^2.

The gripper itself has to respect some specifications too:

R6 weight: < 4 kg;

R7 time for grasping/release: < 3 s.

Some of the specifications may be satisfied depending on the number of grippers used (R1 to R5). Moreover, some of them are requirements of the project, so they have to be respected (R1 to R4).

3.5.1 Intrusive grippers

At the present two workers pierce the jute sacks with four hooks to grasp and handle them. The hooks, whose average diameter is 4 mm, leave small acceptable holes on the jute sack.

Intrusive grippers are frequently used in sacks handling or in food handling. The Schmaltz Gripper [31] is a gripping system used for the handling of flexible, non-rigid components or materials. It is also used to grasp objects which cannot be grasped by using vacuum, e.g. fabric sheets, textiles, foam materials. Its gripping behaviour is achieved by the intrusion of the needles within the fibres of the object. The same principle has been also adopted in food industry to handle frozen fillets of fish or meat [53].

Kazerooni [54] uses of two rotating rollers able to entangle the textile of the sack. The two rollers come into contact with each other and with the sack to be grasped. The rollers start counter-rotating and the sack textile is dragged by the friction forces. When a certain quantity of the sack is between the rollers, the sack can be lifted. The working principle is similar to what happens when trousers come into the bicycle chain.

Kirchheim et al. [55] described a gripper supplied with four claw-systems with three concentric claws per system. The claw systems move vertically and rotate at 90° degrees. The edge of the claw pierces the jute, while the roto-translational motion produces the form closure. The gripper is really tough, but it requires powerful actuators.

This very short state of the art in coffee sacks handling showed that the four grippers listed above are similar, respectively, to fish-hooks, forks, pull-over mill and a corkscrew.

3.5.2 Designed grippers

The database [51] has been clustered and a limited number of concepts has been extracted, prototyped and tested on real-scale coffee sacks. Moreover they exploit principles which are more reliable than the ones of the existing grippers, and better interface with the jute sacks. They are hereby described, and Figure 3.8 shows the grippers together with their inspiring source.

Sewing Gripper A helical metallic wire is sewn, thanks to an electric motor, on the jute sack. Once enough spires are inserted into the material, the sack can be pulled out. To release the objects, the spring is unsewn by the electric motor. This gripper, even being intrusive, does not damage the jute significantly, since the small dimension of the multiple holes created there.

Inflatable gripper It is an intrusive gripper which changes its geometry to achieve the grasping. A deformable membrane, surrounded by a braided sleeve, is inflated to switch from the insertion/extraction to the grasping configuration. The working principle is similar to the cited stent. The main advantage of the pneumatic air actuation are velocity and reliability.

Cam gripper The grasping is achieved thanks to the contact between two or more metallic retractable shelves, and the inner surface of the sack. The gripper is inserted into the object with the shelves in the retracted position, then they are elongated and the object is pulled. This gripper presents a high-reliable grasp and small dimensions.

Reverse Scissor A rod with two shelves aligned with its axis is inserted into the object. Then the shelves are rotated and blocked in an opened position. The main advantage (demonstrated by the use of a bigger protptype) is the reliability of such a grasping system.

All the prototyped grippers (except the reverse scissors gripper that was made in ABS by rapid prototyping) demonstrated good grasping capabilities and a maximum pulling force varying from 200N to 350N. The holes generated into the jute sack remained within the specifications even if a miniaturization process is necessary in the case of inflatable gripper and in general can be appreciated also in the other devices.

Figure 3.8: Some of the devices prototyped and developed.

This Chapter was partially based on the following publications:

- G Fantoni, D Gabelloni, and J Tilli. Concept design of new grippers using abstraction and analogy. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 227(10):1521-1532, 2013. [3]

Chapter 4

Selection Process

This Chapter analyzes the selection process used for the choice of grasping systems in many projects developed during the PhD course, but it can be obviously extended to any other field of invention, for the selection of concepts of objects or services. We can distinguish between top-down methods, when the input is a set of concepts to score and the output is a rank of the concepts, and bottom-up methods, when the user has the description of the grippers and the choice is based on his personal opinion. Simplifying the problem, it is possible to say that the bottom-up methods report more information, but have a higher level of subjectivity, while the top-down methods analyze only the properties of interest for the single case study, but with a higher level of objectivity.

4.1 State of the art and integration with Design by Analogy

The methods analyzed in Section 4.1.1, Section 4.1.2 and Section 4.1.3 are basically the state of the art for concept selection, even though many other methods are available for industrial and academical use.

The selection process is the step that allows the user to choose which concepts, from the set of ideas conceived during the conceptual design phase, he has to continue investigating. It is no sense wasting energy by developing too many concepts at the same time. It makes more sense, instead, to invest time and resources in the development of one, or at most *a few* concepts, in order to have less solutions but of higher added value. So, while Design by Analogy tends to generate as many concepts as possible, the selection process goes in the opposite direction, eliminating the idea not to consider, at least for the specific case in analysis. Concepts generated can still be used in databases for future works, since they can be used in analog projects but with different boundary conditions.

4.1.1 File method

The first method used during the PhD studies was the *file method*. It was mainly used for organizing new concepts developed by the research group and already existing grippers for the RobLog project. The *file method* consists of an information sheet of each concept. It contains the most important information for the area of interest, including bibliographic references in order to facilitate the acquisition of more detailed data. It is conceived for helping the user in identifying if the system described in the file can be used for his goal or not.

This is a bottom-up method, since it gives detailed description of each concept, but still leaves the responsibility of choice to the user. This selection method thus leaves margin for subjective evaluation, but it is really helpful if the set of concepts to decide within is small. In fact, the user has not an immediate vision of which are the concepts that better satisfy his needs, but can gather much more information that can be used also for different projects.

The information contained in the file can vary depending on the type of object. Since the *file method* has been widely used for the sorting of grippers for the RobLog project, hereinafter will be referred to this specific case, once again taking into account that the method is valid for whatever field of research and industry, only varying the information contained in the datasheet.

Usually, the first information included in the datasheet is the name of the gripper or of the grasping principle. The following lines report the image (when available) of the system, the grasping principle, the description of the system and how it works and the references. Many other information can be added, like the use of keywords or the decomposition of the functioning using functional words for the implementation in automated or semi-automated systems.

As said above, the template for the File method classification can vary significantly depending on the purpose of the classification. For instance, the table used for classifying a gripper for the RobLog Project is shown in Figure 4.1. In the specific case it was of interest to describe the functioning of the gripper using functional verbs and keywords, rather than indicating which was the working principle. The main advantage of this selection method is that it does not require the prototyping of concepts, since no scores are required for filling the files, even though the testing of the concept can help in improving the accuracy of information contained in it.

4.1.2 Matrix method

The *matrix method* is a qualitative way of classifying concepts. It has also been used by Fantoni in his recent CIRP Keynote paper [56]. In the columns, the main properties of interest are reported, in order to check if the concept is able, and in which qualitative level, to satisfy them. It is a top-down method, since it returns an overview of the concepts collected in a table, thus allowing a direct comparison of the alternative solutions. Like the *file method* it does not require the testing of the prototypes, since scores can be assigned at a qualitative level.

This method is also at the basis of the expert system described in Section 4.2, since it provides the information the system uses for gripper selection from the database.

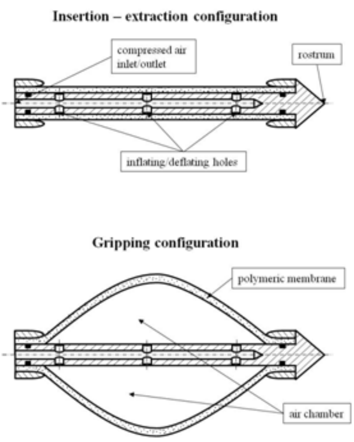
An example of matrix is shown in Figure 4.3, where each line refers to a gripper or grasping principle, while the columns indicate, in a qualitative way, the capability of grasping objects with well defined properties. In some case the match between line and column is a *True or False* output (T or F in the table). In other case it can be described in a more articulated way, such as *very low*, *low*, *medium*, *high* and *very high* (respectively VL, L, M, H and VH). In addition to the properties of the gripper, other fields report the references that may facilitate the user in finding more information.

As already said above, since the scores are qualitative or boolean values, it is possible to assign a value to each concept without the need to build any prototype, even though the testing of prototypes could be helpful in assigning more accurate scores.

4.1.3 Weighted matrix

The problem of selecting the best option among a set of alternatives, can be identified as a general Multiple Attribute Decision Making (MADM) criterion. Usually this method present the following main characteristics [57, 58]:

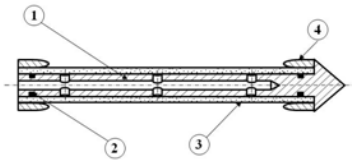
- multiple but finite number of alternatives;
- a level of achievement of the attributes is associated to each alternative;
- final selection of the alternative is realized by a comparison between attributes.



The Expanding Gripper is a very compact gripping system.
Its gripping behavior is achieved by the expansion of an elastic membrane due to the air pressure on its inner side.

At one side of the Chassis (1) there is a rostrum that allows easy penetration into the object to be grasped. In the insertion/extraction configuration, the Elastic Membrane is perfectly fitting the Chassis. On the other side, the Chassis is connected to the Compressed air line. The inner duct of the Chassis distributes the compressed air to the inflating/deflating holes. Air is compressed by an external compressor and, when it flows inlet, the Elastic Membrane expands inside the target. The grasped object can be translated since the Elastic Membrane e is expanded under the effect of Air Pressure. To release the object, the compressed air streams out and so the elastic membrane contracts up to adhere completely to the chassis.

Blue = functional verbs
Underlined = key components
~~Crossed~~ = not considered functions/component



Structural description of the gripper:

COMPONENTS	DESCRIPTION
1. Chassis	supporting structure. It is the compressed air line housing and provides the location of the gaskets (2)
2. Gasket	prevents air leakage
3. Polymeric membrane	its deformation is responsible of the gripping action
4. Holding journal box	ensures the performance of the gaskets (2)

Figure 4.1: The File method used for classifying a gripper for the RobLog Project.

The MADM criterion is a top-down method, since starting from a set of alternatives it returns a ranking of the alternatives. In this case it is necessary to test at least the pretotypes of the invention, since each property of interest has to be scored for each gripper. The advantage is a higher level of accuracy and a lower level of subjectivity, while on the other hand is high time consuming and may require a small investment for the building of pretotypes.

Until now, the MADM problem solving is done, for concept selection processes, following two methods with a different level of accuracy. The first method is more qualitative, such as the one presented for the selection of grippers for automated handling of non-rigid parts by Seliger [59], and still implies a considerable influence of human factors on the spotting of the final solution. More analytical and automated systems have been developed, based on the TOPSIS method, like the ones proposed by Agrawal [60] and Bhangale [61]. For these systems the output is a numerical ranking of the solution. However, while the first system developed by Seliger uses an user-friendly approach, the second ones are very complex and the result may still be affected by the user's sensibility.

The *Simple Additive Weights* (SAW) method [62] reduces the influence of subjectivity on the result of the output. A *Decision Maker* (DM) assigns importance weights to each attribute. To reflect the DM's marginal worth assessment within attributes, the DM also makes a numerical scaling of intra-attribute values. The DM can obtain a total score for each alternative by multiplying the scale rating for each attribute value to the importance weight assigned to the attribute, then summing these products over all the attributes. After the total scores are computed for each alternative, the alternative with the highest score (the highest weighted average sum) is the one prescribed to the DM. The attributes and their votes are provided by a high number of evaluators, with the weights chosen by the specific DM. Different scales can be adopted: linear (e.g. 1, 5, 9) and logarithmic (e.g. 1, 3, 9). The group of evaluators is intended to be heterogeneous and consisting of people with different experience in the specific considered field (for example engineers, technologists, production managers, marketing managers). The higher is the number of evaluators, the lower is the subjectivity of the ratings. To further reduce subjectivity, people who consciously or unconsciously can lean toward the choice of a particular gripper (e.g. the inventor) have to be excluded from the evaluation process.

More recently, other approaches for new products development are the ones proposed by Montagna [63], where the author investigates the integration of tools that facilitate communication, the interpretation of different individual visions and collective problem structuring with tools that analytically study the process activities of new product development. Montagna proposes a *hybrid approach* for the systematic integration of tools from different perspectives, where typological decision-aiding situations are recognized and modeled, and where context and communication in design are considered.

The method described above has been applied to the RobLog case (Section 5.1), that will be analyzed in Section 5.1.

4.2 Expert system for grippers concept selection

Because of the wide variety of objects manipulated in industrial processes, many different grippers, based on different principles, have been developed both in industrial and academical field. Gripper choice or gripper design is often considered the last problem to be solved when a process is automatized. In this way the choice is often a compromise solution, or only the most common grippers are adopted to satisfy the task. Given the task to be accomplished and the growing variety of grippers and strategies, the selection of the most appropriate gripper is not only difficult because of the wide variety of existing grippers but because the existence of incompatibilities with some requirements characterizing of the operation. Thus a certain level of rejects due to bad handling may be accepted even if they are caused by the erroneous choice of the gripper.

For an industrial company or a research team in a research institute the adoption of a new kind of gripper could improve the duty cycle of the operation, the reliability of the whole system and reduce the cost. The present work investigates a methodology for supporting the selection of the grippers able to accomplish a determined task.

4.2.1 Background of expert systems for grippers selection

Since human beings are very familiar with object prehension, the process of automatizing the grasping of an object is often underestimated. In fact when objects have to be grasped in an automatic way, many problems arise: many depend on the object physical properties (e.g. porosity and deformability), but also the conditions in which the object is fed and the characteristics of handling, positioning and releasing increase the complexity of the gripper choice. Parts correctly fed require a less versatile gripper, while in bin picking situation the gripper has to properly grasp pieces with different positions, orientations, part tangling, etc. Similarly, high accelerations, reorientations, high precision releasing etc. during the handling phase, increase the constraints in the gripper design or choice.

The main methods for Design For Assembly (DFA) are the ones proposed in [64–66]. The candidate observed many workers during assembly to compute assembly times, handling difficulties, physical and geometrical characteristics of the parts, insertion difficulties and other aspects of the assembly phases. Moreover they interviewed many experts in order to understand how to overcome specific assembly problems, and finally arranged all the relevant information in the DFA framework.

The central problem of any new DF-X is the definition of the key design parameters influencing the quality of X. Such parameters should supply indications about a good design and must be easy to be measured in the first conceptual phase of the product development. Parameters must also be objective, accurate and easy to be understood [67].

Many of the solutions adopted in DFA techniques have been useful during the development of the present work, in particular issues related to *Handling difficulties*, *Feeding problems* and *Placing* represented the baseline of the analysis. Another valuable contribution comes from the DFH (Design For Handling) techniques, which aim to redesign the object in order to be easily handled from automatic systems [68].

Although the grasping phase is already taken into account in the DFA, a specific tool to evaluate alternatives grippers does not exist nowadays. Some preliminary efforts have been done by FESTO, that developed a selection system for its mechanical grippers.

A general tool that helps the designer in the selection of the proper gripper in case of objects with different dimensions, characteristics, and handling constraints does not exist at present. Its development implies many issues, such as the identification of key parameters, the organization of the grippers in a database, the analysis of correlations among parameters and the collection of design rules.

4.2.2 Methodology

The methodology works interacting with the user through a series of questions concerning the object, the handling operations and other possible requirements. It also aims to help the user into the selection of the suitable grasping principles relying on a predetermined set of parameters and rules.

Parameters, which describe the problem, have been investigated, defined and finally selected with the purpose to consider all the phases in which the gripper is involved: feeding, grasping, handling and releasing. Also the robot which manipulates the gripper influences gripper capabilities and therefore its proper choice. However, this introduces another degree of complexity which cannot be evaluated at this stage of the analysis.

4.2.2.1 System Logic

A deep analysis of the DFA techniques [64] helped to define part of the structure, the logic and the parameters connected to warnings and advice.

In Figure 4.2 the decisional steps of the methodology are briefly synthesized. Steps involving releasing strategies and compatibility check are mainly for micro-parts. In fact, in assembly processes dealing with micro-components (components with a size in the range between 10 μm and 10 mm) the adhesion forces (electrostatic, Van der Waals, surface tension and viscous forces) are usually neglected. Thus gravity and inertial forces [69] become less relevant than at the macroscale. In fact the releasing phase of a micro object could become really challenging due to adhesion between the object and the tool [70] thus requiring specific releasing strategies. Fantoni and Porta [49] collected the main releasing strategies at microscale and defined the compatibility between releasing strategies and grasping principles.

The parameterized description of the problem (filled by the user) and the set of rules (gathered by the literature analysis) constitutes the input, as shown in Figure 4.2. The input is responsible for the exclusion of unfeasible grasping principles and releasing strategies which are automatically selected from pre-defined lists. Then the compatibility between grasping principles and releasing strategies is double checked in order to avoid improper selection of grasping-releasing couples. The output is composed of the list of appropriate grasping principles together with possible warnings, advice and environmental requirements. Furthermore, for each selected grasping principle, a list of specific minimum requirements is given in order to enable automatic searches into the gripper database.

4.2.2.2 Parameters

Parameters can be assigned to two different macro categories: the first one describes the object properties, while the second describes the operation.

The first macro category includes physical and geometrical properties of the workpiece. The second one is divided into three categories:

- placing (e.g. high precision alignment);
- feeding (e.g. oriented/unoriented state of the fed object);
- handling (e.g. lifting, moving, reorienting).

Parameters can be Boolean or multi-valued. Boolean parameters, e.g. sensitivity to liquid, can assume two opposite values: True or False. Conversely,

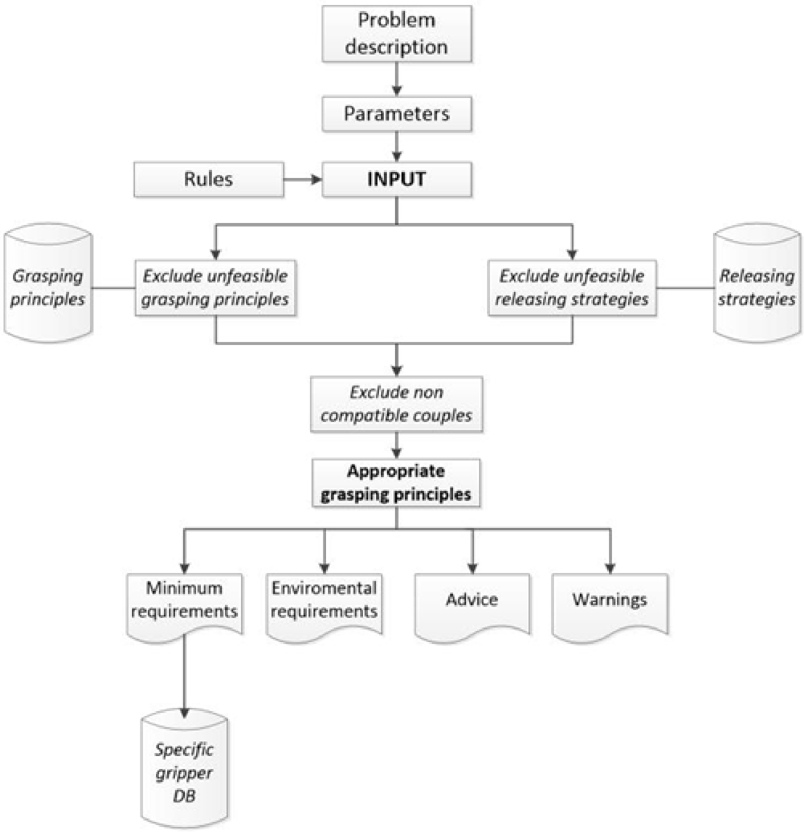


Figure 4.2: Scheme of the logic of the expert system.

multi-valued parameters, e.g. stiffness, are defined to evaluate different levels of the considered parameter (at least three different levels: Low, Medium, High). A correlation analysis between parameters allowed to verify the coherence, to establish a proper order and to avoid possible contradictions.

However, some parameters cannot be evaluated in the input phase, such as the grasping direction and the need of a monitoring system, since they are strictly linked to the specific grasping principle adopted and therefore recursive.

In Table 4.1 parameters are related to physical and geometrical properties of the object, or with the operation phase where they are mostly involved. Even if parameters have been studied in order to be decoupled and to belong to only one category. However in some cases this has not been possible (e.g. stiffness is related both with physical and geometrical properties).

Many of the parameters are self-explaining, while others require the definition of their application field: Hygienic requirements concern the types of products which have to meet specific standards about contamination levels allowed; Sensitivity represents how an object can be influenced by different elements, such as liquids, dust, heat etc.; Predetermined position is needed to establish whether the system knows the exact object position; Regular curved surface has been introduced in order to define if the surface, even if not planar, is suitable for grasping; Toughness evaluates both traction and compression resistance. Furthermore, it is necessary to distinguish between Oriented state, which represents whenever the workpiece is fed already oriented or not, and Orienting, which implies that the gripper has to change the workpiece orientation into a different state than the initial one.

4.2.2.3 Rules

At this step the methodology needs for a specific set of rules. Rules work according to the problem described through the set of parameters and can be organized into three different categories:

- Exclusion rules: they exclude one or more grasping principles or releasing strategies;

- Warnings: they warn the user about how the operation should be done or what should be avoided. For instance recommend to avoid high accelerations, or the warn about the need of a monitoring sensor when dealing with very fragile objects;

- Advice: they advise the user about the opportunity of redesigning the workpiece in order to make it more suitable for automated handling.

At this stage the rule list counts around 200 items: mostly exclusion rules.

4.2.2.4 Gripper Database

Two hundred and fifty papers have been collected in a database. Each paper has been matched with the parameters shown in Figure 4.3. Each cell contains the value of the parameter, if the experiment shown in the paper presented such an information, otherwise the corresponding cell was left empty.

Generally papers describe a specific scenario where a novel gripper is tested with a small set of possible objects. Therefore it is not uncommon that many parameters cannot be easily deductible, then the table results to be quite sparse. This, is partially mitigated by the high number of papers contained in the database. The lack of standardized data in technical documentation represents the counterpart from the industrial side. This limit becomes more relevant when dealing with the most recent and innovative grippers or grasping principles, making a detailed, complete and coherent population of the database not possible.

Reference	Type	Size	Weight	Density	Shape	Roughness	Slippery	Stickiness	Toughness	Stiffness	Object shape can change	Porosity	hydrophic	conductive	Ferromagnetic	Symmetry	Presence of holes	Planar surface	Regular curved surfaces	Wet	Holes on the grasping surface	Hygienic req.	Sensitivity to scratches	Sensitivity to liquid	Sensitivity to water	Sensitivity to charge	Sensitivity to stain	Sensitivity to dust	Magnetic sensitivity	Sensitivity to heat	Sensitivity to acceleration	stacked	tangled	oriented state	know position	Orienting	Acceleration	Aligning	Inserting
[10]	Capillary	micro	VL	VL	Sphere	VL	F	F	L	VH	F	VL	T	F	F	T	F	F	T	F	F	F	T	F	F	F	F	F	F	F	F	F	F	/	T	F	/	F	F
[19]	Needle	macro	L	M	Prism	L	H	L	VL	L	F	L	F	F	F	/	F	T	F	T	F	T	F	F	F	F	T	T	F	T	T	F	F	/	T	F	H	F	F
[21]	Vacuum	macro	M	L	Cylinder	VL	VL	VL	M	VH	F	VL	T	F	F	T	T	F	T	F	F	F	T	F	F	F	F	F	F	F	F	F	F	/	T	F	/	F	F
		macro	M	L	Sphere	L	VL	VL	H	L	T	L	F	F	F	T	F	F	T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	/	T	F	/	F	F

Figure 4.3: Matrix for the classification of grippers.

4.2.2.5 Case studies

The reliability of the proposed methodology has been validated through two case studies: the first one is a standard pick and place operation of a simple mechanical part, while the second one concerns a more complex scenario: the object is a fish fillet and the operation misses an appropriate feeding process.

Exemplary case The object to be manipulated is a steel cube of edge length of 51mm. On the faces there are very small drilled holes, whose area covers more than 50% of the total surface available. The weight of the object is 330 g.

The selected grippers for the required operations are the ones belonging to the following categories:

- friction two fingers;
- friction jaw;
- magnetic.

Other grippers have been excluded mainly because of the shape and the density of the object. Others, such as the suction ones, have been excluded because of the presence of holes. Since the diameter of the holes is 2 mm, thus expansion grippers cannot be used for grasping.

It is interesting to note how three fingers grippers have been excluded, even if belonging to the friction ones, since the grasp is not stable because of the object shape.

Validation - Food For the validation of the methodology a fish fillet has been chosen since it embodies a series of characteristics (such as fragility, deformability, sensitivity to contamination, wettability) that makes it not suitable for automatic grasping. The fish fillet size is 50×65×25 mm and weighs approximately 80 g.

The operation consists in a pick and place where the object is fed through a conveyor, in a random position and orientation, and subsequently it is placed on another conveyor without any specific orientation. The selected grippers for the required operations are the ones belonging to the categories in Figure 4.4.

For the friction gripper, a grasping force of 2.35 N has been defined as the minimum value to efficiently hold the object in case of small accelerations during the handling phase. For this type of gripper, some design advice are given, as for example the minimum finger stroke and minimum finger length. Furthermore (i) a vision system to recognize object orientation and position is needed, and (ii) every gripper must also be designed to meet the hygienic standards required. Electrostatic and Van der Waals grippers have been excluded due to the presence of water which significantly reduces their grasping force [71]. Similarly, capillary and acoustic grippers have been excluded due to the low grasping force related to object shape and density.

Validation - Liquid glue Small bags filled with liquid (glue) are transported through a conveyor belt and at the end must be packed in a card box. At the present the packaging operation is performed manually.

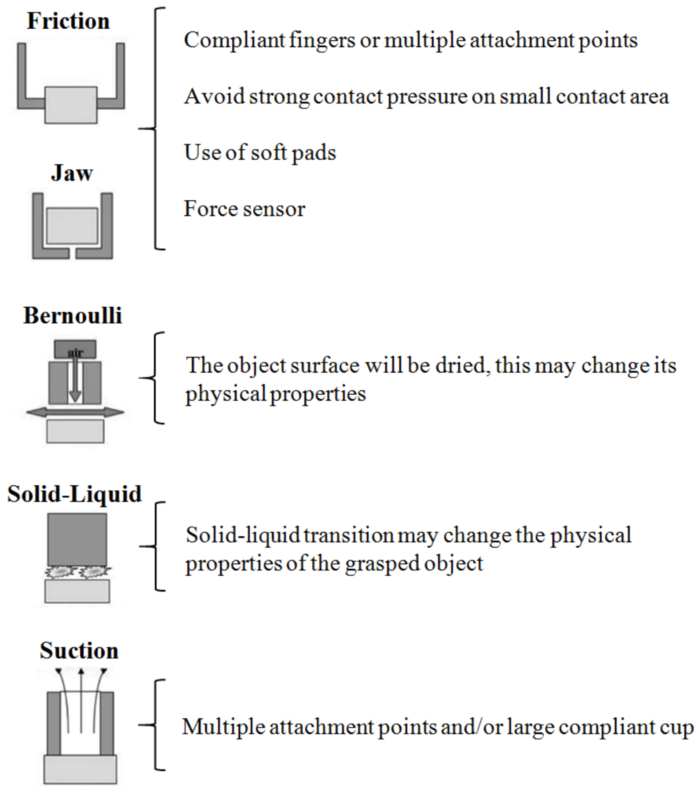


Figure 4.4: Warnings concerning the chosen grippers for the validation case study.

The polyethylene bags are sensitive to scratches, are slippery, deformable, sensitive to heat. The bag size is 300×200×25 mm and its weigh is approximately 450 g. The automatic operation consists in picking the object and placing it in the box.

Mechanical friction grippers have been excluded owing to the deformability of the sack and to the slippery condition of its surface. The presence of water and the industrial environment prevent the use of electrostatic and van der Waals grippers. Bernoulli or Coanda grippers cannot be used owing to the deformability and weight of the object. Also in this case capillary and acoustic grippers have been excluded due to the low grasping forces they can exert.

Vacuum grippers could be adopted even thought their reliability reduces when the object deforms. Form grippers as for example the fork grippers can be adopted. The solution is well known and many industrial end-effectors have forks to handle sacks, bags, etc..

However another gripper seems to have the ability to grasp the flexible bag: the Switle®. It is a friction gripper similar to a shovel. It behaves as a shovel and as a conveyor belt simultaneously. It is formed by an advancing-retracting spatula covered by a textile belt. The Switle®approaches the object, then the spatula advances and the belt is spread below the object without (almost) any friction. The gripper is moved with the object on top, located in the final position and the process is performed backward: the spatula is retracted, the belt is winded on again and the object released. The Switle®grasps and handles very soft and deformable objects (even in sol or gel state) without modifying their shape.

Validation - Lightweight wood inlay For producing inlaying works, wood parts are obtained from foils through laser cutting. Each single part has to be grasped and located in the right place to form the final inlay.

The main problems are: the parts are rigid but tangle with the surrounding elements (parts or debris), the only access is from the top and the surface is partly porous. Mechanical fingers and form grippers cannot be used owing to the presence of lateral parts. Electrostatic and electromagnetic principles does not work with wood, vacuum does not match with the porosity characteristic. Needle gripper can be used but particular attention have to be paid to scratches and imprints. Thermoplastic glues (Liquid-Solid transition grippers) can be exploited as well as no contact handling systems as for example Bernoulli grippers [56] or ultrasound grippers. Due to the porosity of the part vacuum is not the best choice from an economic point of view but, neglecting the waste of energy it can be successfully used as it has done in case of green tapes in [72].

4.3 Conclusions

In this Chapter, the logic of expert system for gripper selection is presented. Even if the case refers to gripper selection, this logic can be extended to any other case where the selection process has to choose a set of possible solution among a list of alternatives included in a database. Obviously, for different cases, the set of rules and parameters change depending on the field of use. At the present moment the system adequately defines the grasping principles capable to perform the required operation together with some fundamental recommendations. However, finding a way to evaluate every possibility, including the variability of the objects, still requires further study and work that could be done iteratively. Since the system is based on a set of rules that can be easily updated, in future it could work as a self-learning system. This turns into an increase in terms of effectiveness and efficiency.

Many other selection methods, or systems for organizing prototypes have been analyzed during the studies, and three of them, the most used for the PhD activities, have been presented above. Some of them, like the file method, are useful for listing the properties of a concept, while other are more suitable for the selection of concepts from a set of alternatives. It is possible to distinguish between a top-down and a bottom-up approach: the first one, which includes the *weighted matrix method*, starts from a set of alternatives, and by setting some parameters and analyzing the properties of the concept, returns a ranking of the alternatives. It is then suitable for a numeric output, since it tries to limit the subjectivity of the user during the selection process. These methods are really powerful, but usually cannot disregard the test phase of pretotypes, since a numerical score of the characteristics of interest is required.

Other methods, like the *file method*, belong to the bottom-up selection process: starting from the analysis of each alternative, the user gather information about each concept. By operating this way, the choice can be made considering all the main aspects of interest of each alternative. One of the main drawbacks is the subjectivity of the user in the choice.

Between the two approaches described above, a third methodology, denominated *matrix method*, is useful for classifying grippers in a way that is more intuitive than the *file method*, but less detailed than the *weighted matrix method*, since it is based on qualitative scores of the properties of interest. Since scores are qualitative, this classification and choice method can avoid the test of concepts and can be based only on assumption of the concept functioning.

Table 4.1: List of the parameters related with the corresponding categories.

	Object		Operation		
	Physical	**Geometric**	**Feeding**	**Handling**	**Placing**
Weight	✓				
Size	✓				
Density	✓				
Porosity	✓				
Slippery	✓				
Stickiness	✓				
Hydrophobic	✓				
Hygienic req.	✓				
Sensitivity	✓				
Conductivity	✓				
Ferromagnetic	✓				
Wet	✓				
Stiffness	✓	✓			
Shape can change	✓	✓			
Roughness	✓	✓			
Toughness	✓	✓			
Shape		✓			
Symmetry		✓			
Presence of holes		✓			
Hole for grasping		✓			
Planar surface		✓			
Regular curved s.		✓			
Stacked			✓		
Tangled			✓		
Oriented state			✓		
Known position			✓		
Orienting				✓	
Acceleration				✓	
Aligning					✓
Inserting					✓

This Chapter was partially based on the following publications:

- G Fantoni, S Capiferri, and J Tilli. Method for supporting the selection of robot grippers. *Procedia CIRP*, 21:330–335, 2014. [4]
- J Tilli, A Brando, and G Fantoni. Gripping device for heavy and deformable materials handling: Concept, design, selection and test. *Procedia CIRP*, 21:373–378, 2014. [5]

Chapter 5

Case Study

This Chapter presents a selection of the projects carried out during the PhD studies. Each section presents a project whose output was the manufacturing of a prototype, and highlights the problems that were encountered during the manufacturing and the test of prototypes.

5.1 The RobLog Project

Processes requiring the handling of heavy and deformable objects are becoming more and more common in the sector of production and distribution of goods. Common examples of deformable items are cardboard boxes, tires and coffee sacks, whose manipulation is generally conduced manually, since automated systems able to deal with them are really challenging to be developed. Therefore, occupational safety, workers' diseases and economical problems arise.

This issue is getting so important that the European Union has financed the RobLog project [15], which supports the development of a completely automated container unloading system.

5.1.1 Object to grasp

One of the most challenging goods to be unloaded are coffee sacks, since they weigh up to 75 kg, and are made of jute sacks filled up to overflowing. Due to these characteristics, the human labor is a high cost factor and, combined with unhealthy working conditions, makes automated solutions highly desirable.

Thus, the objective of this work was to design a set of concepts and to select the best ones to be engineered, exploiting a simple but effective procedure. To establish a repeatable procedure, the inner and outer materials, the dimensions, the weight have been fixed: the tester is a jute sack filled with coffee beans, whose dimensions do not exceed the bounding box 900 mm width, 600 mm depth and 300 mm height, and a weight of about 75 kg. Furthermore, the maximum diameter of the hole that can be created on the sack is fixed in 15 mm.

5.1.2 Concepts

As said above, one of the main drawbacks about coffee sacks grasping is the absence of a significant number of reliable grippers available on the market for this kind of good. The small number of concepts that can be found in literature does not allow the use of MADM methods for the selection of grippers, neither the expert system proposed in Section 4.2 (also strongly based on scientific literature and technical documents). Thus the authors decided to develop a series of concepts, in order to build a database and to apply the method proposed in Section 4.1.3. The technique used for the design of the grippers is the one described in Chapter 3 and based on the *Design for Analogy*.

The prototypes illustrated in Fig.5.1 are described below, and are intended to be used for grasping tests, useful to evaluate the capabilities of each gripper to grasp and to lift or drag the heavy and deformable objects which are present in the RobLog project scenarios.

Parachute and umbrella gripper These grippers exploit the interaction between their surface and the inner material (in case of the parachute gripper) or their surface and the fabric of the sack (umbrella gripper) of the object to be grasped. The first consists of a tough fabric and wires, while the second is realized like the inner structure of an umbrella.

Frontal rotatory gripper The system consists of an external cage rotating around the main axis of the gripper. Three inner stapled cylinders rotate both around the same axis of the cage and around their own axis. The rotatory speed around their axis is lower than the one around the main axis, so that the staples does not damage the jute.

Sewing gripper A coil metallic spring is sewn, using a rotatory electric motor, on the material to be grasped. At the same time the spring translates along its axis. The coil is engaged both with the surface of the target object and with a driving support.

Cam gripper It is an intrusive gripper, whose grasping property is due to the contact between two or more metallic retractable shelves of the gripper, and the walls of the object to be grasped.

Reverse scissors gripper The gripper consists of two hinged shelves which can rotate. When the shelves are closed (that is, over layered one to the other), the gripper can be inserted into the object. Then the shelves are rotated into the open position and kept firm.

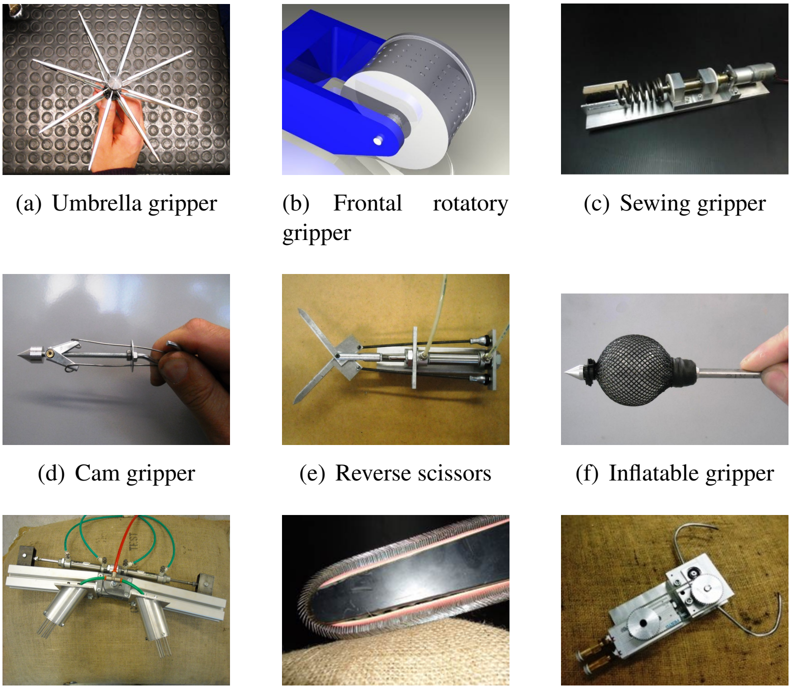
Inflatable gripper The gripping behavior is achieved by the expansion of an elastic membrane due to the air pressure on its inner side. In the insertion/extraction configuration, the elastic membrane is perfectly fitting the chassis. When the gripper is inflated, the elastic membrane expands inside the object grasping it.

Actuated angle needle gripper It is inspired by commercial solutions, which are used for the grasping of fabrics and textiles, such as the Schmalz gripper. Extending needles pneumatically actuated extend from two cylinders, penetrating the surface to be grasped. An actuator varies the angle between the axes of the two cylinders to tight the grasped surface.

Conveyor gripper and Hook stapled tissue The contact surface of the good to be grasped slides directly over the rolling elements (*conveyor gripper*), or is carried by an interposed layer of material (*stapled tissue*). The system is pushed toward the target while the conveyor or the stapled tissue moves, pulling the object onto the conveyor system.

Linear and rotatory double hooked A linear actuator is connected by a slide to two crank mechanism that end with two hooks. The resting position for the hooks is the opened one and, once the system is actuated, the hooks rotate around their axis, thus grasping the target.

Another concept developed is the *Shovel gripper*, which uses four translating plane elements, pneumatically actuated, with alternate motion. The shovels move in opposite direction by groups of two. Triangular shaped profiles



(a) Umbrella gripper
(b) Frontal rotatory gripper
(c) Sewing gripper
(d) Cam gripper
(e) Reverse scissors
(f) Inflatable gripper
(g) Actuated needle gripper
(h) Hook stapled tissue
(i) Rotatory double hooked

Figure 5.1: Concepts of the Gripper.

are mounted on the translating elements, resulting in a different friction behavior of the translating elements in the two opposite directions (low friction while entering, high friction while extracting). The singular gripping element is shown in Figure 5.2.

Among the concepts presented above, the ones to be developed have been selected through the use of the SAW method described in Section 4.1.3, to determine the most promising concept to be developed.

The parameters which generally influence grasping are widely discussed in [56, 59, 73]. In this particular case, the parameters taken into account are related to: (i) graping capabilities, referring to the ability of the gripper to grasp a certain type of material (jute in the present case); (ii) duty cycle, which considers the time for grasping and release; (iii) damages on the grasped object, that represents the maximum dimension of the hole created on the grasped surface, if any; (iv) influence of environmental factors such as presence of dust

Figure 5.2: Single element of the Shovel gripper.

and humidity on grasping reliability. The scores considered for each parameter are the average of the scores given by the evaluators. The average smooths the unaligned votes while the mean "opinion" is considered the central point of the assessment.

All the data have been modified so that the highest is the value of a certain property, the best is the ranking. For instance, the duty cycle has been considered as the inverse of the time needed for a certain operation, thus the highest value is the one of the gripper with the minimum duty cycle. The values that can be assigned to votes and weights are summarized in Table 5.1.

The maximum value of the weights does not alter the value of the weighed scores, while the minimum weight is very low but still nonzero. On the other hand, the scores are distributed on a logarithmic scale, except for the lowest value, which is low but still nonzero. This is necessary because of the mathe-

Table 5.1: Values chosen for the votes and weights to be assigned.

Votes		Weights	
9	good	1	very important
3	medium	0.1	important
1	bad	0.01	neutral
0,1	not suitable	0.0001	insignificant

Table 5.2: Ranking of the grippers. The symbols meaning is the following: ●= highly recommended ◑= recommended ○= not recommended

Ranking	Evaluation	Gripper
1	●	Shovel gripper
2	●	Actuated needle gripper
3	●	Inflatable gripper
4	●	Linear hooked
5	●	Hook stapled tissue
6	●	Cam gripper
7	◑	Reverse scissors
8	◑	Frontal rotatory
9	◑	Hook gripper
10	◑	Sewing
11	◑	Needle gripper
12	◑	Rotatory hooked gripper
13	○	Umbrella gripper
14	○	Parachute gripper
15	○	Conveyor

matical algorithm beyond the selection process method, which would suffer a sparse matrix.

The final score of each gripper is the sum of all the weighed values of each gripper. However the numeric value of the selection has been converted into a symbolic output in order not to influence the user. The numeric output of the selection has been converted, in order not to influence excessively the user, into a symbolic outcome, which is helpful for the selection of the gripper.

As it can be noticed from Table 5.2, few grippers belong to the *highly recommended* class, and among these, the one chosen for the development was the Shovel gripper. A picture of the prototype is shown in Figure 5.3. The prototype has been manufactured and tested, in order to evaluate its grasping capabilities.

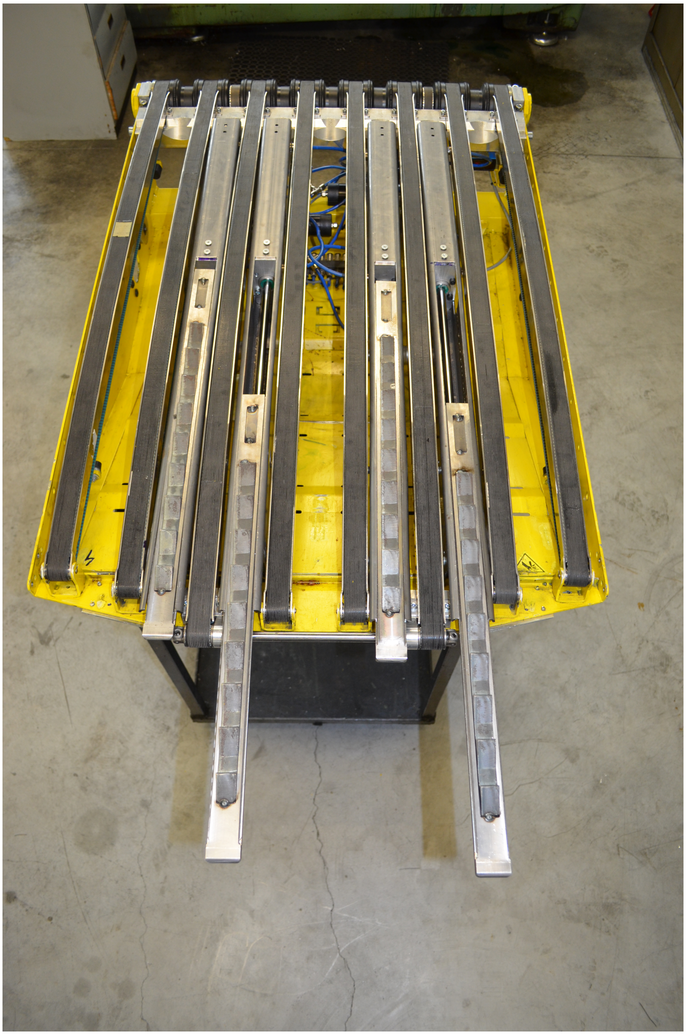


Figure 5.3: Prototype of the Shovel gripper.

5.2 Jamming finger

The goal of this work was to create a prototype of pneumatic actuator based on jamming technology to be used in robotic manipulation. The actuator belongs to the class of Pneumatic Flexible Actuators: the pressure is used to control the bending of the gripper while the jamming technology is used to increase its stiffness. The idea was generated with the Design by Analogy described in Chapter 3, and the prototyping phase aimed at validating the suitability of the concept for the research purposes. The work presents the characterization of a pneumatic actuated finger with a jamming system to increase its stiffness. The actuator is composed of two active chambers responsible for the bending and a third one where jamming happens. An increase in terms of force vs. displacement is expected comparing the jamming finger to the standard one.

5.2.1 Background

Nowadays a new class of robots and gripper is emerging: soft robots pneumatically actuated. Actually, even if some examples of inflatable grippers can be found in the market (Figure 5.4a) many applications appeared in the last ten years. Soft pneumatic grippers for handling fruits and delicate objects as in [74] (Figure 5.4b and Figure 5.4c) have been followed by many examples where the number of fingers increases [75]. Actually, thanks to a single source of actuation and few valves is possible to control also complex multi-finger structures [76] (Figure 5.4d). A review of them appeared recently in [75].

Pneumatic flexible actuators are often located in sets of bellows organized in regular patterns where elastic structures perform one-directional (pushing) action each. Through the composition of their movements both steering and bending can be achieved. They are either made out of a very thick walled rubber tube or they require external reinforcement to appropriately direct force in longitudinal direction. This type of actuation is used only rarely for robotic actuation. One of the most famous is the flexible microactuator (FMA). It has long tradition: in 1991 Suzumori et al. [77] developed this new type of pneumatic rubber actuator with 3 degrees of freedom (DOF) whose mechanics have been analysed theoretically and through finite elements [78]. Suzomori et al. adopted the micro actuator in a pneumatic four finger hand that demonstrated interesting capabilities of both pinching and power grasping.

Such a structure and actuation strategy has been used also during the last years in several pneumatic hands, but the full potential of the technology has been exploited at industrial level in colonoscopies for examples by Era Endoscopy S.r.l. [79]. For such a reason we decided to use the mass produced actuators by Era Technology.

The jamming gripper [80] is formed by one or more elastomeric chambers filled with granular materials. It is characterized by the possibility of changing its state: from soft and deformable to rigid, depending on the vacuum applied inside the gripper itself. Actually the vacuum compacts the granular material contained inside the chambers, increasing the contact force within the grains. The highest is the contact force, the most rigid the gripper becomes. The gripper (often in form of a single balloon) is deformed around the object to be grasped while it is in the soft state. Then vacuum is created, and the gripper becomes rigid, enabling the grasping of the object. The most interesting feature of the jamming grippers relies on the ability of grasping many different shaped objects since it mix form closure (soft state) with force closure (jamming state).

Another type of jamming gripper is the jamming gripper for roof tiles developed at BIBA. This gripper has to handle batches of tiles, prohibiting the relative movement between the tiles themselves. The end-effector has a two fingers which pulps are build up by very tough tubes, filled with granular polymeric pellets, and connected to a vacuum ejector. The two halves of the gripper are moved to the batch, making them to adapt to the shape of the batch itself. The air is removed from the tubes, and the contour is fixed. This way it is possible to create a universal form closure independent from the shape of the grasping object. Recently, Stletz et al. (2010) presented a Jamming Modulated Unimorph (JMU) actuator (Figure 5.4e). It is composed of a single linear actuator and a discrete number of jamming cells, that steer the actuator when activated selectively. That way the 1 degree of freedom (DOF) linear actuator has been turned into a multi DOF bending actuator. Even if the JMU application is oriented to locomotion of soft robots, the numerous analogies at structure level with the presented fingers have to be underlined. Actually both the JMU and the jamming finger are cylindrical actuators with three radial chambers and make use of jamming technology. However, while in JMU the jamming is used to steer the actuator, in jamming finger it is used to increase finger stiffness while inflation drives the steering.

5.2.2 Structure of the finger

The main structure of the finger is manufactured by Era Endoscopy S.r.l., and consists of the terminal part of the instrument for colonoscopy developed by the company. The outer chamber of the finger is made of a silicon rubber

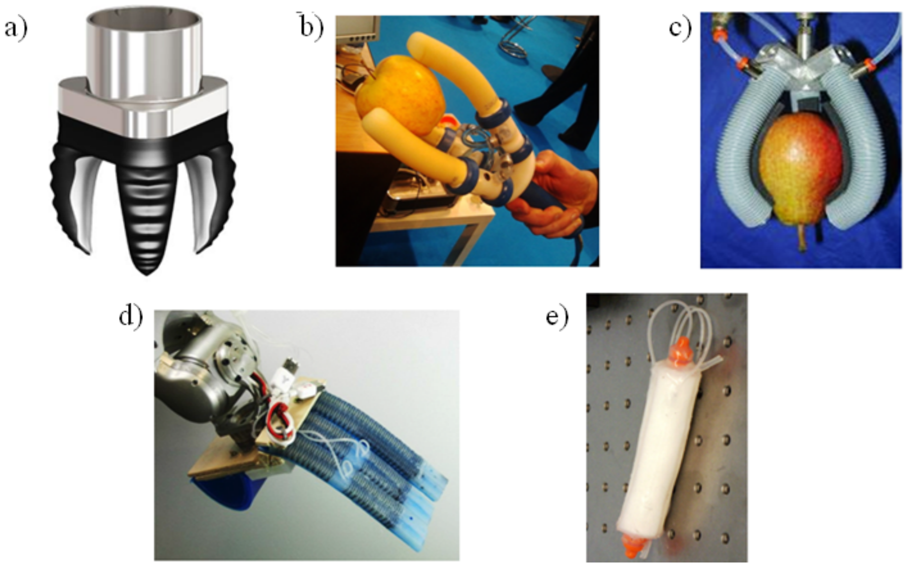


Figure 5.4: (a) 3-fingers Hygienic Design gripper; (b) 3-fingers Hybrid Gripper; (c) 3 fingers fruit-harvesting hand; (d) 5-fingers compliant hand based on pneumatic actuators; (e) Jamming Modulated Unimorph (JMU) actuator.

tube, reinforced with a built-in fiber inside the outer chamber. The body of the finger has three longitudinal chambers, each chamber being 120° of the circumference. The structure of a finger is similar to the one proposed by Suzumori et al. [77].

Two of the chambers are used for the actuation of the finger through the use of compressed air. The enclosure direction depends on the pressure exerted in each chamber, but for these experiments, the same pressure is applied in both of them. The third chamber is filled with granular material, and is responsible of the jamming part of the gripper. A permeable membrane confines the grains inside the chamber, avoiding the obstruction of the channels for the air extraction. When air is extracted from the chamber, the granular material compacts itself, then the finger changes its behavior, becoming stiff.

The outer membrane is modified in correspondence to the chamber responsible of the jamming behavior. To allow the silicon to collapse on the granular material contained inside the chamber, the outer membrane is made thinner, so that the coil is not included any more inside the silicon matrix (Figure 5.5b and Figure 5.5c). When vacuum is applied, the outer membrane compacts the granular material, making the finger stiff. Three tubes come out from the base of the finger. The two tubes for inflation of the chambers are connected to a manometer, so there is the possibility to control the pressure of actuation. The other tube is connected to a vacuum pump for the extraction of air from the jamming chamber.

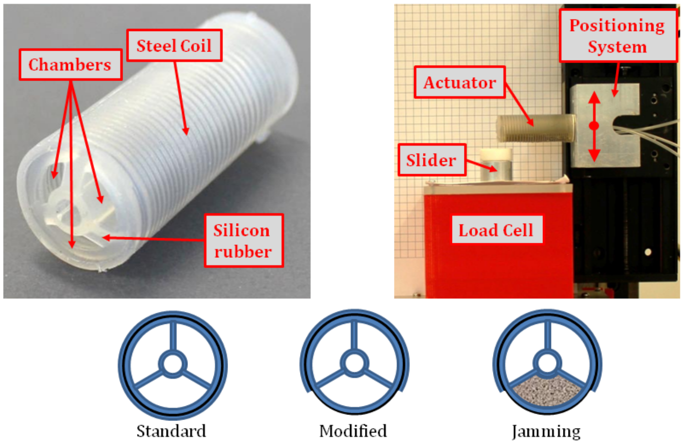


Figure 5.5: *Left* Structure and component of the endoscope; *Right* Experimental set up; *bottom* The three actuators: (a) standard endoscope (b) modified endoscope and (c) jamming finger.

5.2.3 Experimental setup

The experimental setup for testing the contact force between the finger and a target. The target is mounted on a load cell, while the relative position of the finger has three alternatives, as shown in Figure 5.5. The experimental set up is composed of a micro positioning system (Micos VT-80: stroke 100 mm; precision 0.5 µm; bidirectional repetability 10 µm), a load cell, an interface for holding the actuators and a Teflon slider to measure only the vertical component of the force. The experimental device is endowed with a load cell (Micro Load Cell (0-780 g)-CZL616C from Phidgets, Calgary, Alberta, Canada) placed on the basis of the device to record the normal force exerted by the finger interacting with a base plane. The sampling rate of the load cell is 0.01s (100 Hz).

The force measurements have been performed in dynamic conditions. Each actuator was:

1. bent at different pressure levels

2. jammed
3. moved toward the load cell at a speed=0,1mm/sec

The positioning system moves the actuator by 10mm. When the tip of the actuator touches the Teflon slider the load cell starts measuring the force. The Teflon slider reduces the stick-slip effect due to the motion of the actuator against the load cell surface.

Tests have been performed on: a) the standard actuator (endoscope), b) a modified version without granular material inside and c) the jamming finger (see Figure 5.5a-b-c).

To estimate the effect of jamming varying the bending of the finger, two chambers have been inflated at four different pressure values while the third chamber was left passive (Figure 3 left column) or subjected to vacuum (Figure 5.6 right column).

The levels of the actuating pressure were: 0 bar (not inflated) (Figure 5.6a and Figure 5.6b), 0.5 bar (Figure 5.6c and Figure 5.6d), 0.75 bar (Figure 5.6e and Figure 5.6f) and 1 bar (Figure 5.6g and Figure 5.6h). Each experiment has been repeated 5 times. The same experiment has been used to estimate how the jamming increased the grasping force of the jamming finger.

5.2.4 Experimental results

Results from the dynamic experiments performed are shown in Figure 5.7. The pictures show a comparison of the force when no vacuum is applied and when it is. The absence of vacuum puts in evidence the influence of the outer membrane on the maximum contact force that can be exerted. The modified endoscope and the jamming finger generate the same contact force, because of the modification of the outer membrane, while the force created by standard endoscope is higher, owing to the presence of a thicker membrane in correspondence of the vacuum chamber.

Vacuum modifies considerably the behavior of the jamming finger. The standard and the modified endoscopes do not vary significantly the value of force exerted in the same range of displacement, while in the jamming finger the force increases in a significant way.

Values of force exerted at the stroke of 5 mm (with vacuum applied) are reported in Table5.3.

It is interesting to note that: (i) when the actuation pressure is low the predominant effect is due to the jamming principle; (ii) conversely, when the

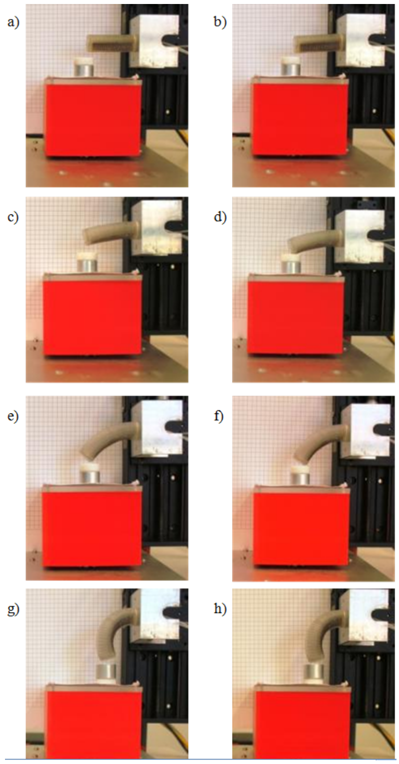


Figure 5.6: Figure 3. Bending at different pressure level. Vacuum not applied (left column): a) 0 bar, c) 0.5 bar, e) 0.75 bar and g) 1 bar. Vacuum applied (right column): b) 0 bar, d) 0.5 bar, f) 0.75 bar and h) 1 bar.

actuation pressure increases the main responsible of the force exerted is not the jamming, but the structure of the finger itself.

Another key reason why the effect of jamming decreases when the structures bend themselves, is the elongation of the chambers. Actually, when the pressure is increased in the inflation chambers, they change their length, modifying also the length of the vacuum chamber. This reduces the effect of jamming, since the volume of granular material contained inside the chamber remains the same, but the volume in which it is contained is modified.

The effect of jamming is important: the comparison of the force exerted by the same structure with and without jamming material inside showed the force exerted is considerably higher when jamming is active.

Moreover the effect of jamming is considerably higher at low bending ra-

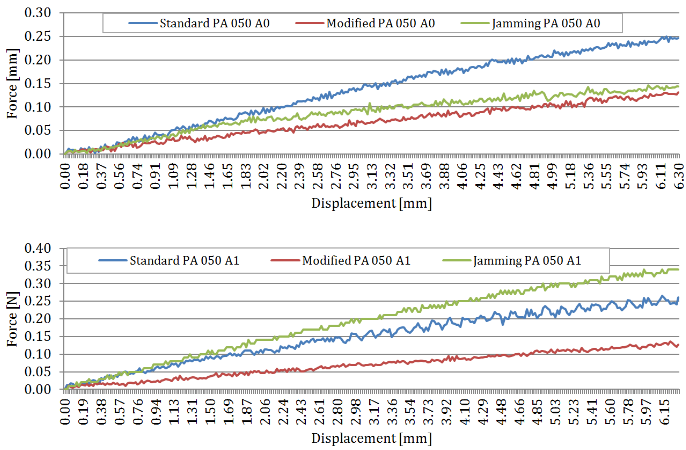


Figure 5.7: Comparison of the force exerted by the finger when vacuum is not applied (top) and when vacuum is applied (bottom).

Table 5.3: Numeric data for the force exerted by the endoscopes and the jamming finger at the stroke of 5 mm (vacuum applied).

	Standard Endoscope	Modified Endoscope	Jamming Finger
p = 0.00 bar	0.29 N	0.20 N	0.41 N
p = 0.50 bar	0.21 N	0.11 N	0.26 N
p = 0.75 bar	0.38 N	0.25 N	0.33 N
P = 1.00 bar	0.42 N	0.31 N	0.34 N

dius of the finger than at high bending ones. In the first case the influence of the structure of the finger is lower than the in the second case, making the effect of jamming more evident.

5.3 NineSigma Project

The research group decided to participate to a proposal of NineSigma [81], where a global engineering and automation company, invited proposals for on-demand switchable adhesion technology. One of the main goals of the project was to create grippers able to rapidly pick up objects on one side, transport and release them. Since the adhesion technology had to be switchable, the release had to happen by reversing the adhesion/gripping effect, or using physical properties of the grasping system in order to release the object. The requirements of the project were the following (citing from the proposal):

- Respond fast and grab or release within at most 1 second, preferable within 0.1 s
- Be activated and deactivated by an industrial standard 24 V DC I/O (conversion to other signals within the solution is also possible)
- Allow the transport and precise positioning of the grabbed objects before releasing
- Allow for single side gripping, e.g. not rely on a mechanical gripping action or have moving parts
- Be able to switch many times (several thousands) without part replacement or extensive maintenance
- Be applicable on solid parts with different sensitive surfaces, e.g. polished, coated or painted, as well as a variety of pliable and permeable objects like textiles, carbon reinforced plastic parts, or other lightweight parts
- Objects from 10 to 250 g in the first step. Higher masses desirable.
- Not damage the objects or leave any traces
- Preferably not use energy during the adhesion phase
- Be safe to use in an industrial environment

The candidate, together with the research group, decided to propose four grasping principles, even if for some of them not all the requirements were satisfied.

The grasping principles proposed are reported in the following sections.

5.3.1 Peltier cell

The Peltier cell is a thin plate made of two different conductors. One side of the cell cools down when a current is made to flow, while the other side warms up. On the other hand, when the current flows in the opposite direction, the cool side and the warm side are switched. This make it possible to quickly freeze and melt liquid in contact with the Peltier cell and the object to be grasped. Videos of the experiments are available at the links [82–85].

5.3.1.1 Transfer to an industrial case

The use of Peltier cells has been used for an industrial case of gripper developed for leather grasping. As it is visible in Figure 5.8

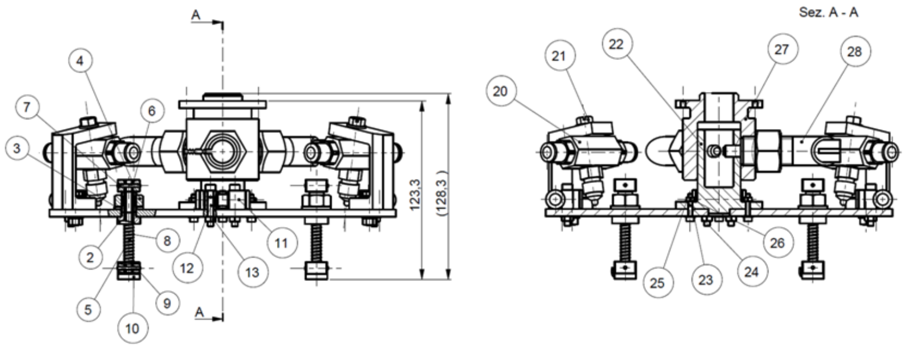


Figure 5.8: The gripper developed for the grasping of leather sheets.

5.3.2 Electrostatic

The electrostatic principle is based on the properties of stationary or slow-moving electric charges with no acceleration. In this case, by creating an electrical field onto a pad, composed of conductive electrodes placed upon a polymer substrate. When the electrodes are charged, astriction between two surfaces subjected to an electrical field is created. Videos of the experiments are available at the links [86–88].

5.3.3 Micro-suction cups

The gripper is a rubber-like pad, which has semi-spheres onto its lower surface. By pressing the pad against the target, air inside the semi-spheres is expelled, thus creating adhesion between the gripper and the target object. One of the disadvantages of this principle is the impossibility of grasping porous objects. For releasing, a strategy for detach the object from the gripper has to be considered (e.g. peeling or the use of external agents). Videos of the experiments are available at the links [89–91].

5.3.4 Chemical adhesive

The chemical grippers consider the possibility of creating adhesion between an object and a silicon-like pad. When the pad is pressed against the target, the microinteraction between the two parts create continuity, thus enhancing grasping. For releasing, a strategy for detach the object from the gripper has to be considered (e.g. peeling or the use of external agents). Videos of the experiments are available at the links [92–95].

5.4 Problematics encountered during the manufacturing of prototypes

The concepts realized presented some limitations: many of the prototypes manufactured for the RobLog project were created using rapid prototyping techniques: the advantage was the short time required for the manufacturing, but on the other hand the mechanical properties were considerably worse than the ones of the same prototypes if they would have been made using other materials or other manufacturing processes.

Also the use of traditional manufacturing processes in some cases did not allow to create complex shapes that may have been desirable for structural reasons or for interface problems.

Looking forward to the implementation of prototyping for industry, another problem is the possibility of creating a large batch production size of many products belonging to the same family, but where each one is different from the others.

This Chapter was partially based on the following publications:

- M Rohde, G Fantoni, J Tilli, and R Mortensen Ernits. A challenge for automation in logistics: gripping systems for automatically unloading of coffee sacks. *4th International Conference on Dynamics in Logistics*, 2014. [96]

- J Tilli, A Brando, and G Fantoni. Gripping device for heavy and deformable materials handling: Concept, design, selection and test. *Procedia CIRP*, 21:373–378, 2014. [5]

Chapter 6

Pretotyping and Prototyping

This Chapter explores the main limitation of the manufacturing processes of prototypes. By observing the problematics related to the construction of the prototypes presented in Chapter 5, the candidate and his research group tried to find solutions to problems concerning time for manufacturing, mechanical properties of components manufactured using rapid prototyping techniques, and cost of manufacturing process, whether the output is a prototype, whether it is the series production of customized objects.

6.1 Problems in the creation of prototypes

Many of the concepts pretotyped or prototyped show some limitations. These can be due to economical or mechanical aspects: the use of traditional materials and manufacturing techniques can lead to the construction of an object whose mechanical properties are similar to the ones of the final object, but on the other hand the time required for building the prototype and can require, depending on the type of manufacturing process adopted, high economical investment. Furthermore, the creation of complex shapes is almost impossible for small production series, since they are difficult to create with traditional machines (e.g. lathe, milling machine), and they would require the creation of molds for the injection of plastic materials or metals. This would result in an investment that is too high for the manufacturing of a prototype.

Contrary to what is observed for traditional machining techniques, rapid prototyping techniques offer the possibility of creating objects having also complex shapes, requiring a limited production time and, depending on the process used, a limited cost for materials. The main drawback of these techniques is the limited performance of the mechanical properties, even if sometimes, depending on the process and the materials used, performance can be comparable to traditional machined objects.

Many studies attempted to improve the design composition for manufacturing processes, like the one proposed by Binnard in [97], whose goal is to provide new design tools that would allow to better exploit the potential of additive manufacturing techniques, and rapid prototyping in general.

6.2 Projects and prototypes realized

One of the main limitations of prototypes realized for the RobLog project was their low structural resistance. Since objects have been obtained using rapid prototyping techniques, their mechanical properties were depending on the technique used and on the material. The main drawback of objects obtained via fused deposition manufacturing techniques is the absence of continuity within the volume of the part, since the object is created by fusing a wire of plastic material. Many authors have investigated this field, attempting to study the layer orientation for improving the mechanical properties [98] or to reduce the time required for building a part and minimize the material used [99]. In this research field there are ongoing activities for the improvement of a Design for Fused Deposition Manufacturing, that aim at optimizing the filament deposition in order to obtain the best mechanical behavior of the component.

Since some prototypes were realized using Selective Laser Sintering (SLS) techniques and Nylon-12 materials, one of the main limitation of its use for the construction of fully reliable prototypes. It is well known that there is a high dependence of mechanical properties of polyamide components on build parameters [100], but the main problem for Nylon-12 was the low Elongation at Break (EaB) of the sintered material, even varying the build parameters. The research group decided thus to investigate some auxiliary process to improve the EaB of laser sintered Nylon-12.

Other problems encountered was the need of creating complex shapes without using expensive tooling methods. With CNC machines, it is possible to shape objects with complex geometries, but material cost can be too high, and sometimes it is no worth using a CNC for the shaping of a pretotype or prototype, depending on the goal of the project. The research group faced the problem of developing a new manufacturing method for the rapid creation of economic molds or shapes for fiberglass deposition.

Finally, another problematic encountered in the industrial field was the series creation of customized appliances. In the specific case, the goal was to create appliances for the orthodontic sector. The problem of customization and mass production has already been faced in many fields of medicine or medical appliance (e.g. modular crutches that can adjust to the height of the patient), but for this case it was not possible to conceive modular objects. Every single object is different from the other, but the production batch size is too high for handcrafted manufacturing of the appliance. The problem to be solved was in this case the creation of a methodology for the series production of fully customized objects.

6.3 Improvement of mechanical properties of Laser Sintered Ny-lon-12

Among the available rapid prototyping techniques [11], SLS is one of the most used processes in the last years, because of the high quantity of materials that can be processed with this method. The work carried out during the period spent abroad at the University of Texas at Austin from July 2014 to December 2014 is described in this section.

Selective Laser Sintered Nylon-12 parts have worse mechanical properties if compared to injected Nylon-12. The analyses performed on SLS Nylon-12 specimens show a high variety of elasticity and tensile strength values, due to the process used for the manufacturing of the parts. The elasticity and tensile strength of SLS Nylon-12 are considerably lower than the ones of injected Nylon-12. The different behavior depends on the different meso-structure of the materials: continuous material with long polyimide filaments in injected Nylon-12, small particles sintered together and short polyamide filaments in case of SLS Nylon-12. This work analyses possible solutions to overfill the gap between the mechanical behavior of the two manufacturing processes, analyzing the crosslinking between Nylon-12 parts at a macroscopic scale. The studies and the solutions found in this work will be the initial step behind the implementation of the techniques in the selective laser sintering machines.

6.3.1 Background of Nylon-12 laser sinterization

Nylon-12 is one of the most used materials in the Selective Laser Sintering (SLS) process. The potential importance of sintered Nylon-12 in industry is demonstrated by the presence of patents related to the manufacturing through the use of SLS machines [101]. Furthermore a wide number of patent [102] covers different aspects of the SLS process and the materials that can be used for building the parts.

Sintered Nylon-12 is widely used in many different fields, e. g. in art for the creation of complex geometries, and for the realization of medical appliances [103]. Besides the theoretical good mechanical properties of Nylon-12 [104], its use in fields where a high reliability on mechanical properties is required is limited by the high variability of mechanical characteristics. The variability of mechanical properties in SLS process is common in all the sintered thermoplastic materials [105]. Zarringhalam studied the process stability of laser sintered Nylon-12, concluding that the main variable property was EaB [106], depending on the type of powder used. Zarringhalam states that the increased molecular weight of the particle is a possible responsible of the ductility. Moeskops et al. [107] highline the difference in terms of EaB and creep behavior within sintered and injected Nylon-12. Moeskops et al. also state that the presence of unmolten regions of particles cause the drop of Nylon-12 mechanical properties.

Some attempts for improving mechanical properties of laser sintered Polyamides have been done in previous works. The effects of electron beam induced crosslinking on Polyamide (in the specific case Nylon-6) were studied in [108]. The authors state that the effects of crosslinking increase the tensile strength and yield stress, while the EaB is decreased.

6.3.2 Methodology of the experiments

Since the high cost of Nylon-12 powder, and the high time consuming process required to set the SLS machine, the methodology taken into account for experiments was the post-processing of laser sintered components. In fact, even if it would have been interesting to consider the effects of chemical additives during the sintering process, the treatment of high quantities of powder and the long time required for setting the machine, process the powder and cool down the powder bed would have reduced the possibilities of testing the specimen in reasonable time and with low costs.

This work analyzes the effects of post processing on sintered Nylon-12 tensile bars. The shape of specimens was the dogbone bar with dimensions according to ASTM D638-02a, and in order to facilitate the external agent penetration, and to evaluate its efficiency, the slicing direction for the SLS process is shown in Figure 6.1.

The post processing treatments taken into account were (i) heat treatment and (ii) chemical treatment followed by heat treatment. The solutions used

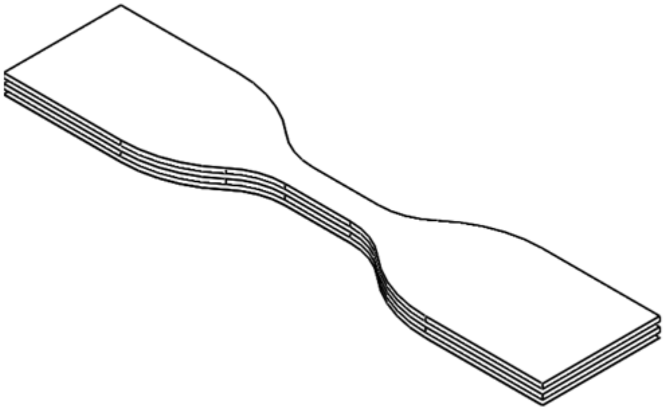


Figure 6.1: Slicing direction used for the SLS process of Nylon-12 tensile bars.

were Boric Acid dissolved in water and an aqueous solution of Ammonium Hydroxide ($NH_3(OH)^-$), while the temperature used for the heat treatment was the one used for the sinterization of Nylon-12 (188°C). It was decided to explore these types of treatment because it was supposed that the low EaB of laser sintered Nylon-12 if compared to the injected one was due to two main factors: (i) the low interaction between the polyamide filaments in the sintered Nylon-12 (Figure 6.2a), and (ii) the presence of discontinuity in the macro-structure of sintered Nylon-12 components (Figure 6.2b).

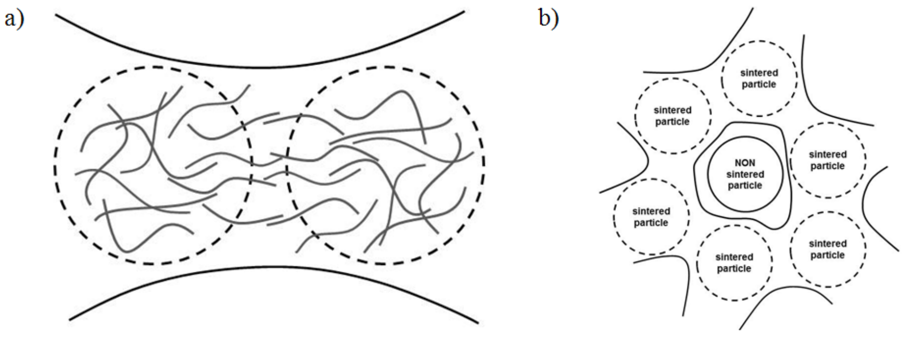


Figure 6.2: (a) Low interaction between the polyamide filaments of two adjacent particles and (b) presence of discontinuous element in the sintered material.

The chemical treatment, by altering the structure of polyamide filaments, is supposed to increase the interaction level between two adjacent particles, chemically or physically, while the heat treatment is the main responsible of the melt or sinterization of the discontinuity elements.

The comparison between the mechanical properties of post-processed sintered Nylon-12 tensile bars with the non-post-processed make it possible to understand whether and how additive materials modify the mechanical properties. Despite the low absorption rate of water based mix [4], laser sintered tensile bars where immerged in chemical solutions before undergoing heat treatment. Boric Acid (H_3BO_3) is well known for its crosslinking mechanism in polymerizing polyvinyl alcohols and silicone oils as shown in Figure 6.3. It has been used for crosslinking of polymeric materials, such as poly(vinyl alcohol) membranes [109]. The intent is to crosslink Nylon-12's amide groups using the $B(OH)_4^-$ molecule obtained when boric acid is dissolved in water. This crosslinking mechanism was investigated for polyamide objects fused together by SLS as a possible approach for improving both the elasticity and tensile strength of sintered parts.

In fact, when Boric Acid is dissolved in water, it accepts a hydroxide group forming B(OH)4-. It is hypothesized that the boric acid reacts with the Nylon-12's amide groups in a condensation reaction illustrated in Figure 6.4.

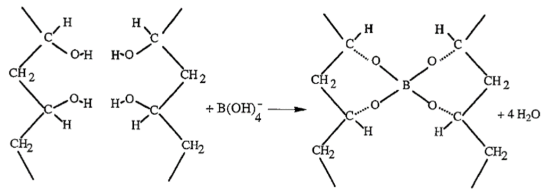


Figure 6.3: Crosslinking of Polyvinyl alcohol by Boric Acid.

Amide groups are known to have a slight double bond characteristic due to the electronegativity of the nitrogen. This resonance is why the amide bond is the most stable of carboxylic acid derivatives and could play as an intermediate in the boric acid crosslinking mechanism (Figure 6.5). This resonance could also account for the improved physical properties of treated parts, forming covalent cross linkages between polyamide strands. This resonance could also account for the improved physical properties of treated parts, forming covalent cross linkages between polyamide strands. This resonance could also account for the change in physical properties in polyamide strands when treated with ammonia. High pH could favor the ionized form over the neutral amide and thus increase interaction between strands via ionic interactions.

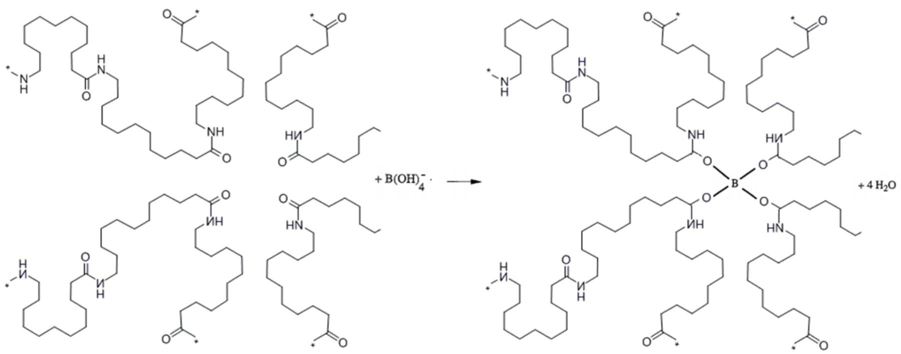


Figure 6.4: Hypothesized chemical reaction of Nylon-12 amide groups and Boric Acid.

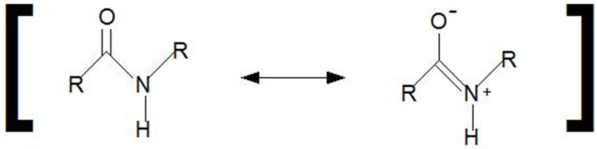


Figure 6.5: Boric Acid crosslinking resonance.

6.3.3 Experimental setup

Tensile bars were built using a SLS machine from 3D Systems®, in particular the model Sinterstation HiQ+HS. A Isotemp®Vacuum Oven Model 282A was used for the thermal post treatment process of the specimen. Even if it is possible to set the temperature with a precision of 1°C, during the experiments it was noticed that the actual temperature in the oven could be different than the set one, with a maximum difference of 5°C.

Specimens were tested using an Instron model 3345 single column testing system, while data were acquired using the testing system software, Instron Bluehill. All the experimental equipment was available at the Freeform Lab at the University of Texas at Austin.

6.3.4 Results and Conclusions

About 40 tensile bars were tested using different post-treatment combinations. As said in the previous sections, the post-treatment process the tensile bars underwent to, were (i) heat treatment, (ii) Boric Acid and heat and (iii) Ammo-

Table 6.1

	Temperature [°C]	Elongation at Break
Non-treated		10%
Heat treatment	180-190	40%-150%
$NH_3(OH)^-$ and temperature	180-190	170%-400%
H_3BO_3 and temperature	180-190	160%-440%

nium Hydroxide and heat treatment. The temperature set for the heat treatment was 185°C, so, considering the error of the oven, was varying from 180°C to 190°C. Some of the specimen tested had to be discarded, since the final result was highly affected from scratches or deformation created on the surface during the warm heat treatment and because of the influence of the texture of the supporting base used in the oven on the final surface of the tensile bar. Values of temperature for the heat treatment and EaB values for each post-treatment process.

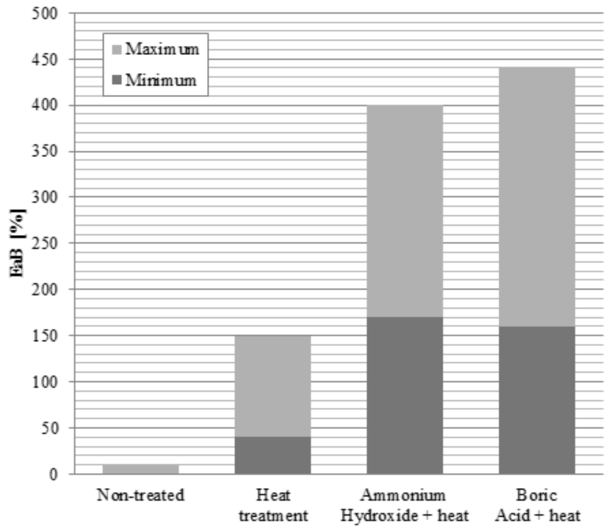


Figure 6.6: Minimum and Maximum values of EaB for tensile bars treated with different chemical substances.

As it is visible from the graph of Figure 6.6 and from the values reported in Table6.1, the heat treatment increases the EaB values considerably. It can be supposed that this is the influence of unmolten elements in the sintered part.

By treating chemically the tensile bar, the EaB values increase up to values that go to the 400% in case of Ammonium Hydroxide, and 440% in case of Boric Acid. It is important to note that the spread between the minimum and maximum values obtained during the tests is very high.

By analyzing the fracture point with the SEM microscope, it is possible to note also how the tensile bars treated with chemicals (Figure 6.8b and Figure 6.8c) have a much homogeneous structure if compared to the tensile bar treated only with heat (Figure 6.8a).

One of the main drawbacks of the post-treatment is the loss of dimensional precision and in some case also of the geometrical properties. This is due to the low stiffness of Nylon-12 when heated up to temperatures close to the melting point. Two solutions, which will be deeply investigated in some future activities, can be used to solve this problem: (i) the pre-processing of powders, and (ii) the creation of a supporting structure for preserving the geometrical properties.

The pre-processing of powders would make the chemical reaction happen during the sinterization phase, thus enhancing the mechanical properties of laser sintered Nylon-12 without the necessity of undergoing to further treatments.

On the other hand it could be still necessary to have a heat treatment. In this

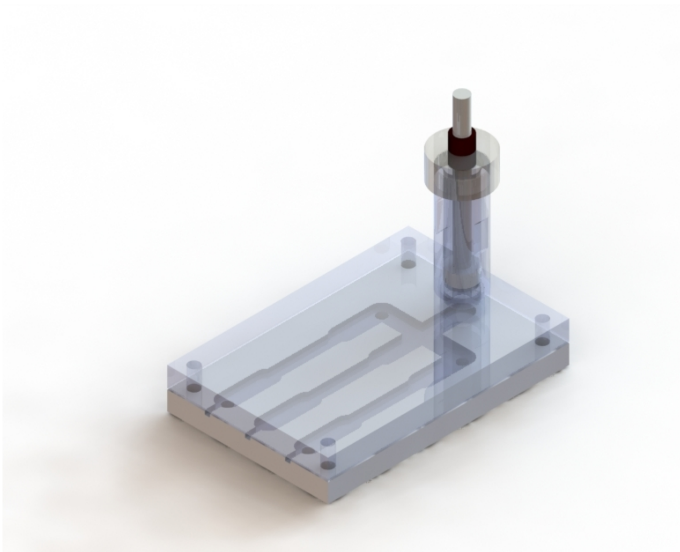


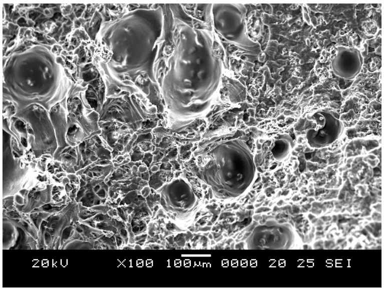
Figure 6.7: The mold for the construction of the injected tensile bars.

case it would be opportune to create a supporting structure, which preserves the dimensional and geometrical properties of the object during the post-treatment process. The material of such a structure has to be thermally conductive, self-supporting at the temperature of heat treatment, and easily removable. Some possible solutions are Silicone and graphite powder.

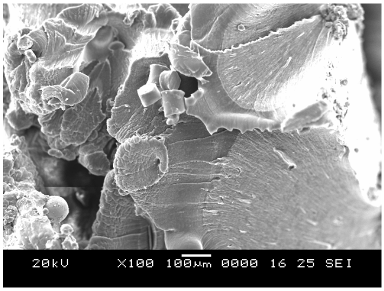
An experimental injection mold is under construction for the evaluation of the effects of pre-treatment with chemical additives to standard Nylon-12 powder. The mold (Figure 6.7) consists of an injection system and of a mold for the creation of tensile bars.

Still, this procedure will not allow understanding the effects of chemical agents on sintered Nylon-12 powder. However it will make possible to study the effects of powder pre-processing, and will allow getting more accurate results because of the reduced deformation due to heat post-treatment. The goal is to compare how the external agents influence the mechanical properties of Nylon-12 from a relative standpoint by comparing the treated material with the non-treated one.

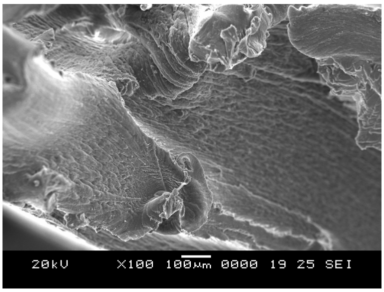
The idea is to transfer the most promising technology to the real SLS process, and compare the results with specimens created from traditionally sintered Nylon-12 powder.



(a) Heat treatment



(b) H_3BO_3



(c) $NH_3(OH)^-$

Figure 6.8: SEM images (magnification 100x) of the fracture point of tensile bars. The treatment the tensile bars underwent to are: (a) heat treatment, (b) Boric Acid and heat treatment and (c) Ammonium Hydroxide and heat treatment.

6.4 Foam-like objects machining using an ultrasound probe

This part of the studies moved from a request from a Surf manufacturing company based in southern Tuscany. The goal was to create an innovative process for shaping foam-like materials, such as Polystyrene and Polyurethane, that is the preliminary step for the final creation of the surf. In fact, the core is then covered with a hard shell made of fiber glass or other light-weight material. The requirements from the company were to create a flexible process, able to shape foam-like materials, without creating (or reducing considerably the creation of) debris and chips.

Once the process has been conceived, the question that came to the head was the following:
is it possible to use the same process for the creation of prototypes? Which are the eventual advantages of using such a process in the prototype manufacturing process?

The answer to this question is the possibility of applying the same manufacturing process for the creation of prototypes, since the good mechanical properties of glass fiber artifacts, the small amount of time required for creating the shape, even for a single object manufacturing and the low costs of the whole process. Another possibility is the implementation of this technology in a more complex process, even in the rapid manufacturing field, the same that happens with the milling operation for Solid Ground Curing [102, pp. 50–51] or the cutting for Laminated Object Modelling [110, pp.139–149].

In the following Sections the analyses performed and the details of this innovative manufacturing process are explained in detail.

6.4.1 Background of ultrasound machining

Expanded Polystyrene and Polyurethane are largely used by hobbyists for manufacturing lightweight model planes, surfboards, but also by artists to create masks, costumes, statues etc. From an industrial point of view surf manufacturers during the design and prototyping phase shape expanded polystyrene blocks by using hot wires and then by milling. They use 3-axes numerically controlled milling machines. Unfortunately the process of milling creates a lot of dust and debris that stick to the milled surfboard.

In order not to affect the following operations (coating with primer, fiber glass deposition and painting), an accurate cleaning operation to remove dust and debris is required. The cleaning operation may result high time consuming and often not easy owing to the electrostatic charges on the debris that sticks on the workpiece.

The possibility of using an instrument often used in different fields (e.g. for joining plastic components) for machining the foam-like materials was thus investigated. A sonotrode originally used for the mixing of chemical solutions has been used for the shaping operation on Polystyrene and Polyurethane blocks. Ultrasound probes are nowadays commonly used for many industrial applications, such as manufacturing processes, food industry and many other fields.

In the case of foam-like materials shaping, a mix of effects, as the heat generated in the contact between the sonotrode and the workpiece and the sound wave pressure, make the foam melt and the machining operation is thus performed. The new methodology combines the effect of heat with mechanical action, and in presence of a fluid and under certain conditions, also cavitation.

Both the in air and underwater machining have been tested and, as it will be visible in the following Sections, each machining process has its own peculiarities, since the heat specific capacity of water reduces the effect of thermal melting and promotes the cavitation, but also freezes the molten material in a rigid structure immediately after it is generated. This effect is also interesting for the machining of non-foam-like materials, like wax, since it freezes and removes the molten material from the machining area.

6.4.2 Uses of ultrasound in industry

In the industrial field, the ultrasound technology is largely used for detecting objects and measuring distances. Other typical applications are in the healthcare sector, in ultrasonic imaging for nondestructive testing of products and structures, in oral care for plaque and tartar removal from teeth, and in many other fields. Of course ultrasound scalpels found many uses in many different fields, from surgery (e.g. maxillofacial surgery [111]) to metal cutting in industry [112].

Recently, a piezoelectric vitrectomy probe able to liquefy the humor vitreous for eye surgery has been patented [113] and the number of patents exploiting ultrasound wave is continuing growing year by year. Industrially, ultrasound technology is widely used in several fields: from micromotion [114] to cutting of materials [115], from cleaning to foundry, from joining and soldering [116] to hard material machining [117], from mixing [118] to material dispensing [119]. Examples, working principles and video material can be found in many websites of Original Equipment Manufacturers. Even if the scientific level is not often high, such sources provide insight of processes that now are no more considered as “non-conventional processes”.

Focusing on manufacturing technology, ultrasounds are used with hard slurries in the so called ultrasonic impact grinding, both for macro and micro machining [120]. The process consists in a vibrating tool oscillating at ultrasonic frequencies used to compress an abrasive slurry between the workpiece and the tool thus inducing small cracks on the workpiece and removing the material from the workpiece itself. This machining process suits perfectly for hard and brittle materials, such as glass, titanium, sapphire, ruby, diamond and ceramics [117]. In ultrasonic welding of plastics, high frequency (15 kHz to 40 kHz) low amplitude vibration is used to create heat by way of friction between the materials to be joined. The interface of the two parts is specially designed to concentrate the energy for the maximum weld strength. In investment casting (known as lost-wax casting in art) [121] reported that solidified parts are broken from the sprue thanks to ultrasonic vibrations.

Recently (in the last 20 years) ultrasonic blades found many applications in food industry since Ultrasounds are suitable for almost all kind of food cutting. Actually, ultrasonic assisted food cutting offers good performance in precision, uniformity and hygiene, and is the perfect cutting technology for a wide range of industries. Other ultrasonic instruments relates to the cleaning systems, both for industrial or private use [122].

6.4.3 Working Principle

Images shown in Figure 6.9, thanks to the signals that derive from electron-sample interactions, reveal information about the external morphology of the samples of Polystyrene:

a) untreated Polystyrene presents a regular structure, with spherical profiles;

b) thermal altered Polystyrene shows a stretched structure, with pseudo-circular holes;

c) in-air machined Polystyrene has a spread texture, in consequence of the fact that polystyrene begins to melt;

d) underwater machined Polystyrene shows a squamous structure, due to the rapid solidification of melted material in contact with water.

Conducting the same analyses for Polyurethane samples, Figure 19 reveals that:

a) untreated Polyurethane presents a smoothed face, with few irregular holes;

b) thermal altered Polyurethane presents a regular hexagonal structure;

c) in-air machined Polyurethane has a soldered texture, due to the spread of melted polyurethane;

d) underwater machined Polyurethane reveals an indented structure, by reason of the rapid solidification of underwater processed material.

From the analysis of the SEM images, it is clear that heat is not the only working principle, otherwise the structure would have been similar to the one shown in Figure 6.9b and Figure 6.9b. Since the texture of in-air machined material is the one shown in Figure 6.9c and Figure 6.9c, the mechanical action has an important role in spreading the softened material over the walls of machined shapes. Figure 6.9d and Figure 6.9d are useful for understanding the action of water in case of underwater machining.

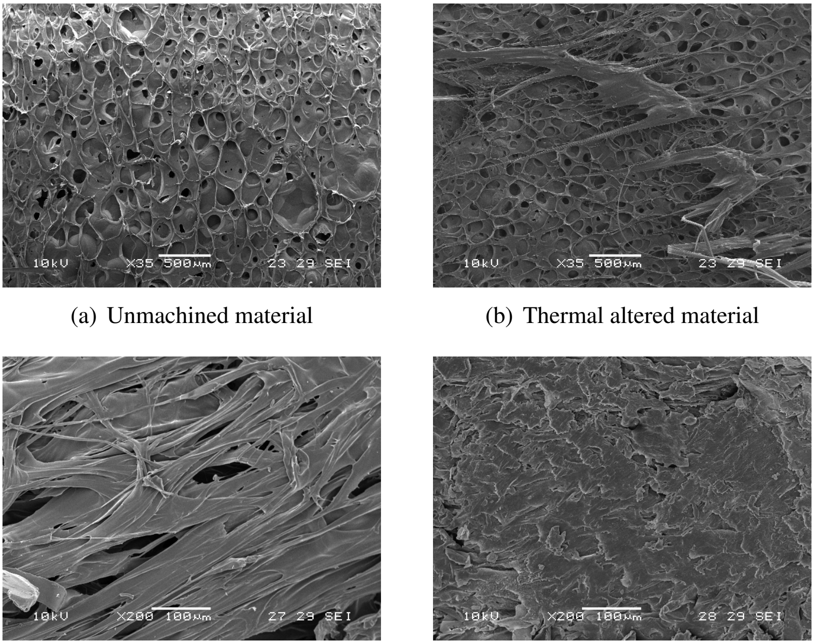
6.4.4 Experimental setup

The goal of the research is to evaluate the feasibility of drilling and milling operations of polymeric foam-like materials using an ultrasound probe. The force-displacement behavior is analyzed and the profile of the samples obtained with this manufacturing process in case of different input parameters and materials are analyzed.

The main apparatus of the experimental setup is the sonotrode. The machine used is the Vibra Cell VCX 130 PB from Sonics & Materials, Inc.. The vibration frequency is constant and it is 20 kHz, while the amplitude can be set within a range from 0 μm to 100 μm. The tip of the sonotrode is cylindrical with a diameter of 6 mm.

The system acquisition experimental setup includes: (i) a PhidgetBridge 4-Input, (ii) a Wheatstone Bridge based sensor acquisition board from Phidgets, Inc, (iii) an off center load cell, modified with shelves for acquisition of compression load, with a maximum nominal load of 3 kg from Celmi s.r.l. and (iv) a translation stage VT-80 from Micos USA having an allowed maximum force of 49.0 N. Force acquisition and the stage control were done using Labview 8.5 using a sample period of 20 ms. The load cell was calibrated using a series of weights starting from 100 g up to 600 g.

Figure 6.11 shows a scheme of the experimental setup for in air machining, while the top view of the experimental apparatus is shown in Figure 6.12. It



(a) Unmachined material

(b) Thermal altered material

(c) In air USM machined

(d) Underwater USM machined

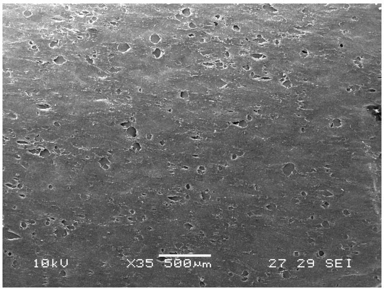
Figure 6.9: Polystyrene surface analyses using the SEM microscope. It is visible how, according to the different working condition, the material surface texture changes, indicating a different working principle case by case.

is possible to clearly observe the translation stage (a) on the left, with the load cell (b) mounted on it. The sonotrode (c) is powered by the Vibra Cell power supply (d). A Polystyrene sample (e) is fixed on the load cell.

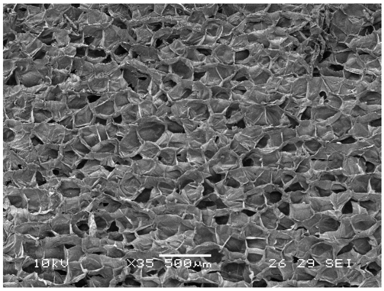
The scheme of setup used for the underwater machining is shown in Figure 6.13, and the real setup is shown in Figure 6.14. In this case The sonotrode (a) is maintained vertically and linked to the translation stage (d) thanks to a specific support (b). A horizontal guide (c) links the stage the vertical structure (e), which is firmly fastened to the frame. A transparent container (g) is located upon a load cell (f). The workpiece is blocked in the container (g) where water is poured until the workpiece (sample) is completely submerged.

Output data from LabView 8.5 were processed in Microsoft Excel files, allowing the comparison of force exerted by the sonotrode during the drilling operations in different working conditions and different materials.

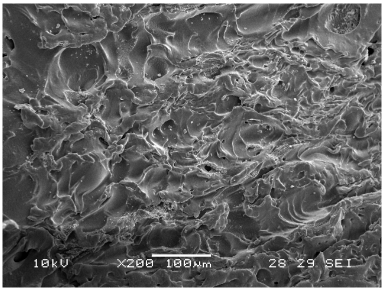
Finally samples Samples were sectioned along the axis of the machined



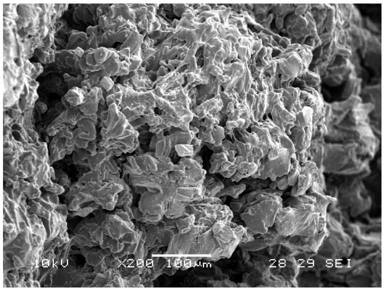
(a) Unmachined material



(b) Thermal altered material



(c) In air USM machined



(d) Underwater USM machined

Figure 6.10: Polyurethane surface analyses using the SEM microscope. It is visible how, according to the different working condition, the material surface texture changes, indicating a different working principle case by case.

hole to analyze the features of the produced profile. White samples (polystyrene) were gold sputtered in a S150B gold sputtering instrument for better resolution. Samples were then examined under a stereomicroscope Wild M3Z in reflected light. Images were recorded using a digital camera directly mounted on the microscope. Images show differences between the investigated features of the sample by using the contrast between the different areas.

6.4.5 In air machining results

The aim of the study is to analyze how input parameters affect the drilling operation in terms of maximum force exerted and quality of the profile of the hole.

In order to analyze the effects of input parameters on the drilling operation, experiments were performed using three constant feed rate values (1 mm/s,

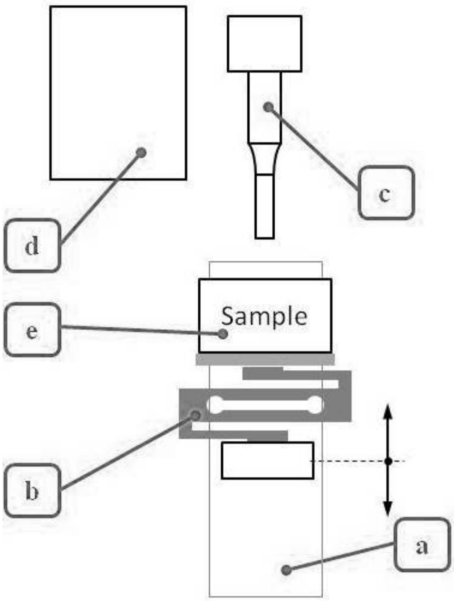


Figure 6.11: Scheme of the experimental setup for in air machining.

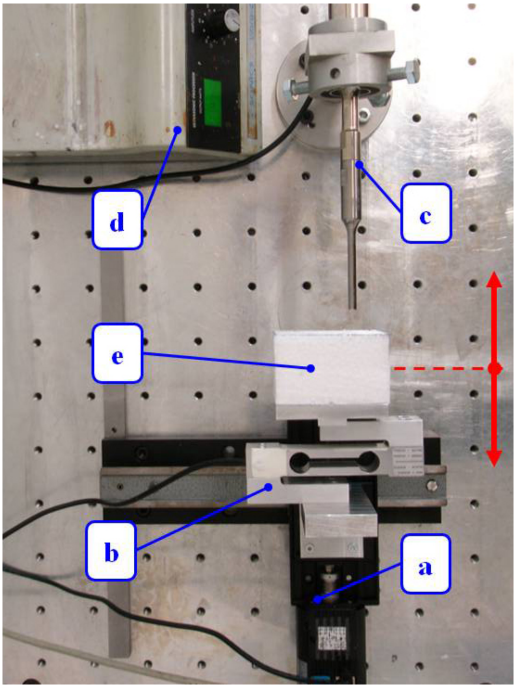


Figure 6.12: Top view of the experimental setup for in air machining.

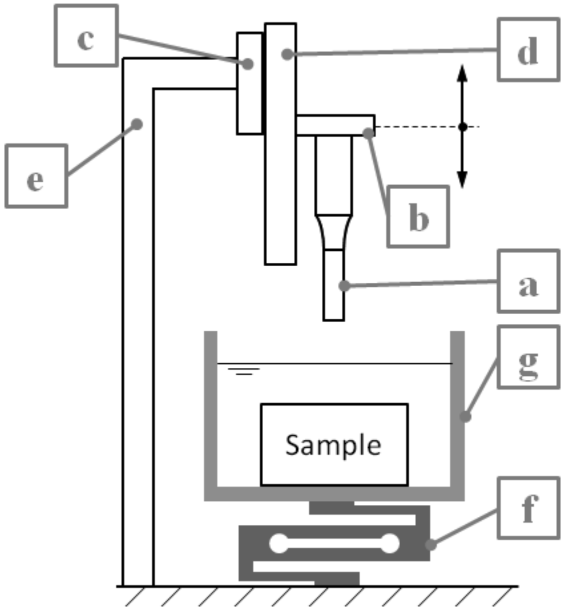


Figure 6.13: Scheme of the experimental setup for under water machining.

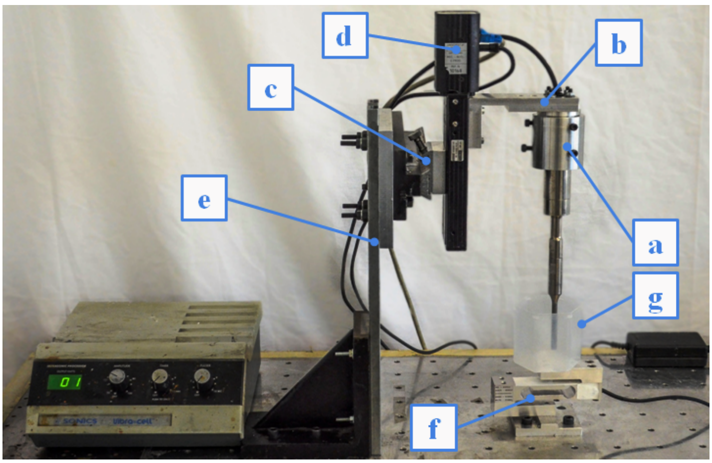


Figure 6.14: Scheme of the experimental setup for under water machining.

2 mm/s and 5 mm/s), and three amplitude of the sonotrode (60 µm, 80 µm and 100 µm) on two different materials. The materials considered for the experiments were Polystyrene with a density of 13.5 kg/m^3 and Polyurethane with a density of 30.5 kg/m^3.

Because of the lower homogeneity of the structure of polystyrene, five polystyrene samples for each input set were tested, while only three samples of polyurethane for each set were tested owing to the higher homogeneity of polyurethane foam. Thus a total number of 45 samples for Polystyrene and 27 samples for Polyurethane were analyzed.

When the tip of the sonotrode is pressed against the workpiece, two main effects occur: the first one is the compression of the material in front of the sonotrode, the second one is heat generation. The tip and the workpiece heat up (the maximum temperature measured during the tests was 47°C) because of friction between the side of the sonotrode and the wall of the hole. One more effect seems to occur, that is cavitation, but more detailed research has to be carried out regarding this aspect. The absence of dust and debris is related to a combination of the pressure and heat generation. In fact pressure is the main responsible of shape forming at least in the first phase of the machining operation, while heat creates a shell around the walls of the hole, having higher density and different mechanical properties.

6.4.5.1 Polystyrene in air

Data analysis shows the force displacement behavior and the maximum force required to the sonotrode to perform the drilling operation for each set of parameters.

It is interesting to note that force increases rapidly during the initial part of the experiment, then decreases to a lower value. The peak is to be attributed to the elastic deformation of material, while the decrement happens in correspondence of the heat generation due to contact between material and sonotrode.

One of the most remarkable results emerging from the data analyzed is the strict dependence of the maximum force exerted from the material structure. Polystyrene macroscopic structure shows the high non-homogeneity level of the material, thus revealing scattered results of maximum exerted force, even using the same working parameters. This is clearly shown in Figure 6.16a, where the maximum load varies from 3.34 N of Sample 1 to 0.73 N of Sample 3 for a feed rate of 5 mm/s and an amplitude of 100 µm. Considering the sample with the highest load value, given a certain feed rate, graphs can be compared varying the amplitude (Figure 6.15). It is interesting to note that the force value decreases when the amplitude is increased. On the other hand, comparing graphs of force exerted at a given amplitude, and varying the feed rate values (Figure 6.16a), it is evident that maximum load decreases when the feed rate is reduced.

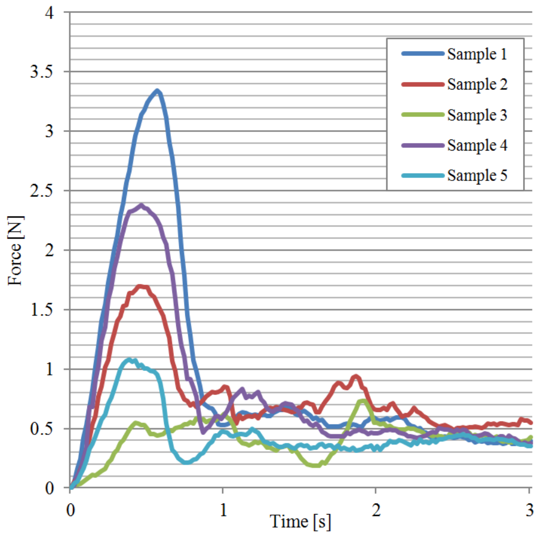


Figure 6.15: Force exerted by the sonotrode on polystyrene samples (v = 5 mm/s, amplitude 100 µm).

The analysis of samples obtained with the same working parameters highlighted the variability of surface finish. This is shown in Figure 6.16b, where three Polystyrene samples obtained with 1 mm/s and feed rate and 100 µm amplitude are compared. However, it is important to note that, even if variable, the average surface quality is almost the same for the same set of working parameters. The tests revealed that no dust or debris are produced during the manufacturing process.

6.4.5.2 Polyurethane in air

Polyurethane has a completely different behavior. Actually Polyurethane foam has a homogeneous distribution of material, thus resulting in a good repeatability of experiments, as shown in Figure 6.17a. The analysis of the plots reported in Figure 6.17b for a given speed confirms the results already obtained for Polystyrene samples. The maximum force exerted by the sonotrode decreases from a value of 5.72 N of the sample obtained with 1 mm/s and an amplitude

Table 6.2: Working parameters adopted for the experiments and number of samples analyzed for each material.

	v = 1 mm/s	v = 2 mm/s
A = 80 μm	3 Samples	3 Samples
A = 100 μm	3 Samples	3 Samples

of 60 μm, to the value of 1.92 N of the sample obtained with the same speed and with an amplitude of 100 μm. Like in the manufacturing of Polystyrene samples, no dust or debris are produced during the drilling operations.

6.4.6 Under water machining results

Because of the contact between the sonotrode and the workpiece, heat is generated during the operation. The presence of water is the main responsible of heat removal from the machining area. In many applications this effect would be desirable, and one of the goals of the work is to investigate if heat removal improves the surface finishing of the machined areas. On the other hand, since the quasi-absence of heat effects, the expected loads are higher than the ones obtained without heat removal. This is the reason why experiments were performed with low feed rate (1 mm/s and 2 mm/s) and high amplitudes (80 μm and 100 μm).

Because of the higher forces expected, the experiment was done only over four different combinations of speed and amplitude, not including neither high feed rate, nor low amplitude of the sonotrode (Table 6.2). Each combination was repeated over three samples. The experiment has been performed also on wax, but 2 mm/s feed rate experiments were not done because of the fragility of the material.

6.4.6.1 Foam-like materials

It is interesting to note that both for Polystyrene and for Polyurethane, force increases rapidly during the initial part of the experiment, then decreases to a lower value, like when these materials are machined in air. The main difference is the force decrement during the second part of the graph: while the peak is to be attributed to the elastic deformation of material, the decrement happens in correspondence of the heat generation in case of in-air machining, and because of a combination of heat generation, cavitation effect [123] and direct contact between sonotrode and workpiece in case of underwater machining.

The data analyzed here seem to confirm one of the result emerged from the in-air machining studies: the maximum force exerted is highly dependent on the material structure. Polystyrene high non-homogeneity significantly influences the profile of the graph and the maximum force exerted, since they vary within the samples machined with the same working parameters (Figure 6.18). Polyurethane has a more homogeneous structure, thus resulting in a lower variability of experimental data within samples machined with the same parameters (Figure 6.19). Considering the effects of working parameters, from the graphs shown in Figure 6.20 (Polystyrene) and Figure 6.21 (Polyurethane), it is clear that both speed and amplitude influence the force exchanged between the workpiece and the sonotrode. Given a feed rate value, when amplitude is increased, force decreases. On the contrary, given an amplitude value, the maximum force exerted decreases when feed rate is reduced.

An important comparison has to be done about the surface finishing of materials, if compared with in-air samples. Considering for instance Polystyrene (Figure 6.22), the dimensional precision of the hole does not change significantly, or is even improved. The single most marked observation to emerge from the comparison between in-air (Figure 6.22a) and underwater samples (Figure 6.22b) is the difference of the heat affected material distribution. In both cases there is a shell-like material surface with altered properties (gray area in Figure 6.22a), but comparing under water with in air machining, the properties of this heat affected area are more homogeneously distributed. This effect is also evident from the analysis of Polyurethane samples (Figure 6.23). The observation of in-air samples (Figure 6.23a) highlighted the presence of highly heat affected zones (lower part of the hole), while is evident the absence of this area in underwater machined samples obtained with the same working parameters (Figure 6.23b). The main difference between in-air and underwater machining is not the dimensional precision, that is comparable, but the influence of heat affected zone.

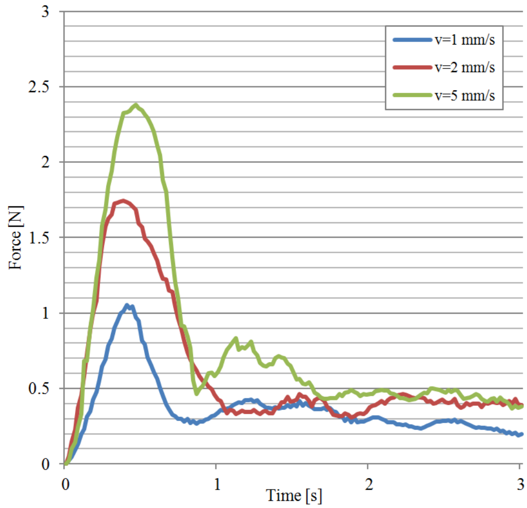
For both Polystyrene and Polyurethane the pattern of the walls is different, because of the different working principle responsible for the operation.

6.4.6.2 Wax

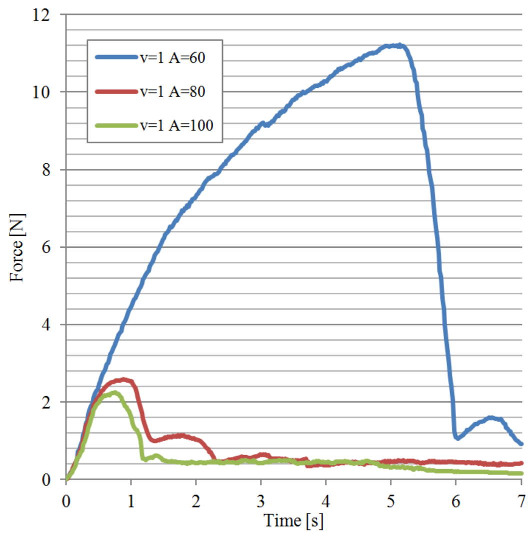
Machining of Wax has also been analyzed. In-air machining of this type of material is possible, but comparing the holes shown in Figure 6.24, underwater machined hole (b) is much well defined than the in-air machined one (a). By analyzing the videos of the experiment (screenshots shown in Figure 6.26), the different phases of the process are evident.

The sonotrode is positioned over the workpiece (a), then the drilling operation starts and wax starts melting (b). Finally wax solidifies and is removed from the working area (c).

Experiments were done only for 1 mm/s feed rate, because of the fragility of wax samples, but the data analysis revealed an unexpected low force exchanged between the sonotrode and the workpiece. This is most probably because of the low melting temperature of wax, that makes heat the main working principle also for underwater machining. In fact, the measured temperature at the interface wax-sonotrode was 43°C, thus allowing to conclude that heat has a big influence on wax working conditions. Figure 6.25 shows the experimental results for samples obtained with an amplitude value of 80 μm. Output data have been filtered to remove the load cell noise, that for the values obtained is visible. The in-air tests have not been performed because of the unacceptable quality of holes created.

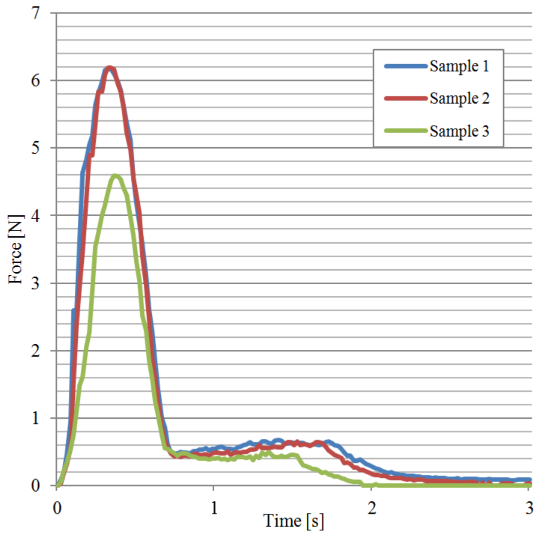


(a) Feed rate influence.

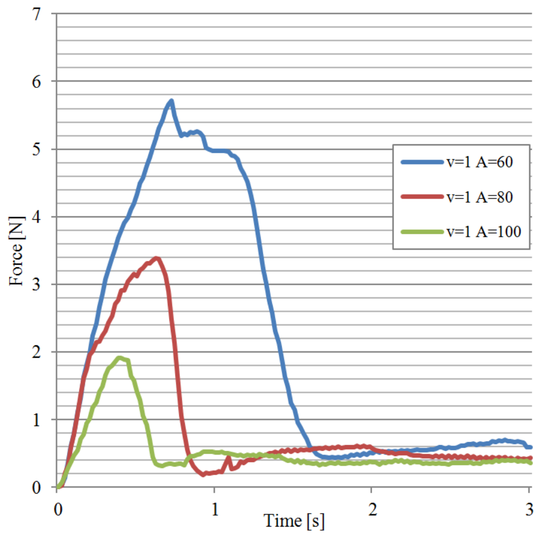


(b) Amplitude influence.

Figure 6.16: (a) Graphs of the average force exerted on Polystyrene samples, varying the feed rate value at the amplitude 100 μm and (b) maximum force exerted by the sonotrode on Polystyrene samples (v = 1 mm/s), varying the amplitude.



(a) Feed rate influence.



(b) Amplitude influence.

Figure 6.17: (a) Force exerted by the sonotrode on polyurethane samples (v = 5 mm/s, Amplitude = 100 µm) and (b) Maximum force exerted by the sonotrode on polyurethane samples (v = 1 mm/s), varying the amplitude.

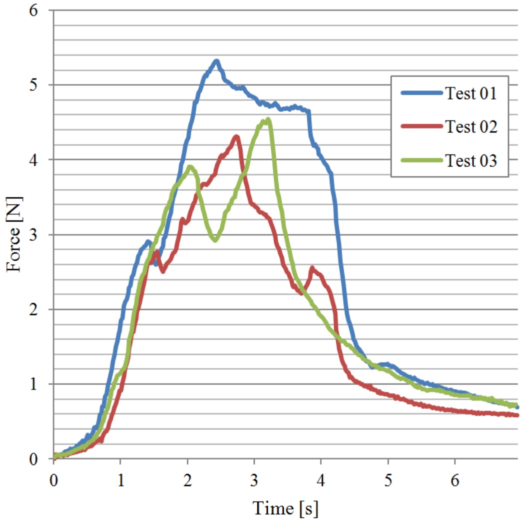


Figure 6.18: Comparison between the force exerted for the same machining parameters (v = 1 mm/s, amplitude 80 µm) on Polystyrene samples.

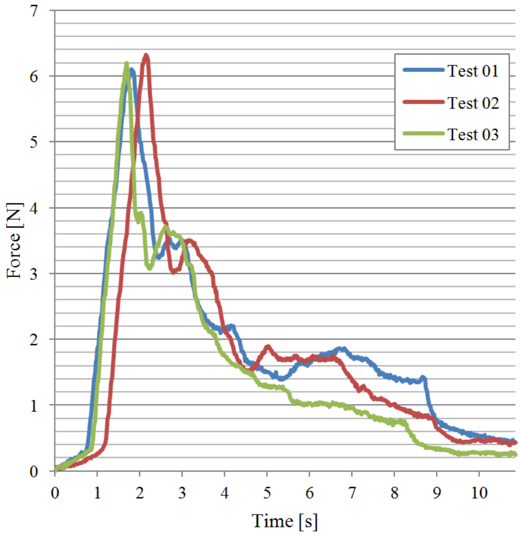


Figure 6.19: Comparison between the force exerted for the same machining parameters (v = 1 mm/s, amplitude 80 µm) on Polyurethane samples.

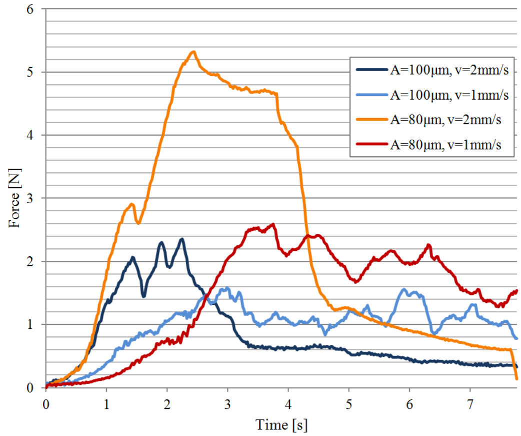


Figure 6.20: Comparison between the force exerted on Polystyrene samples with different working parameters.

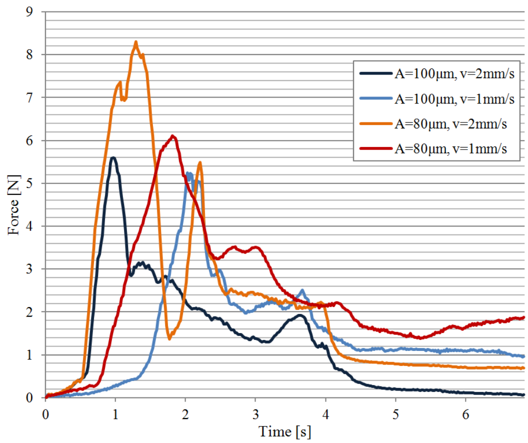


Figure 6.21: Comparison between the force exerted on Polyurethane samples with different working parameters.

a)

b)

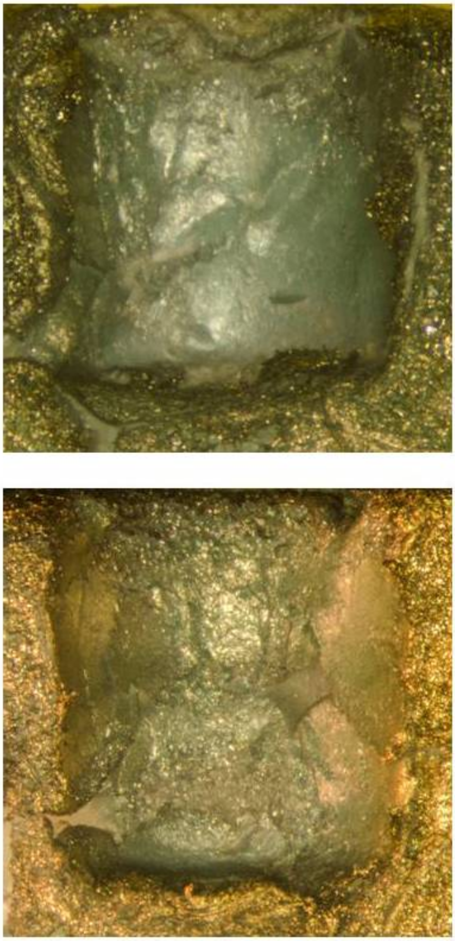


Figure 6.22: Differences between (a) the sample of Polystyrene machined in in-air configuration and (b) the underwater machined sample (v = 1 mm/s, amplitude 100 μm).

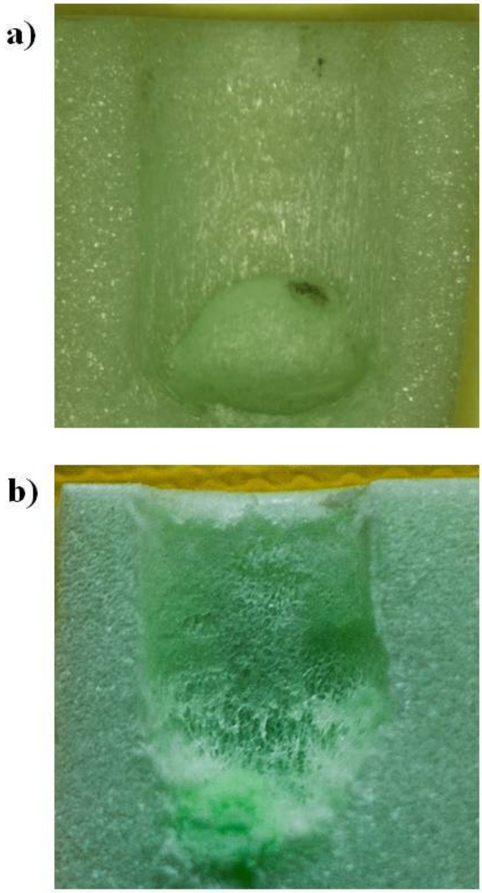


Figure 6.23: Differences between (a) the sample of Polyurethane machined in in-air configuration and (b) the underwater machined sample (v = 1 mm/s, amplitude 100 µm).

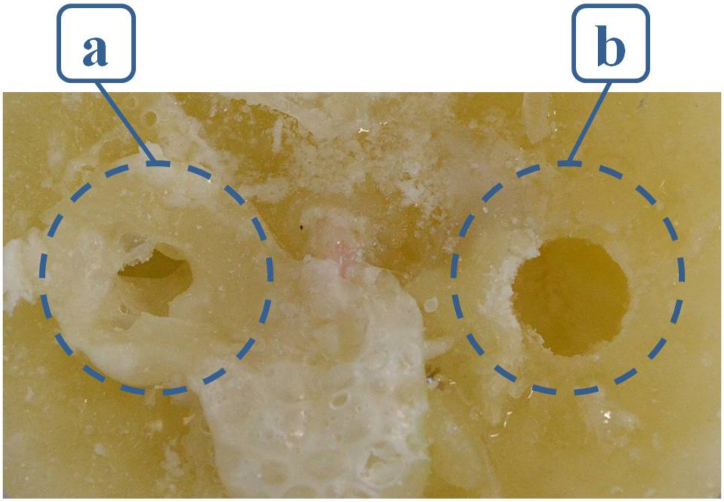


Figure 6.24: Different behavior of Wax when machined (a) in air and (b) underwater.

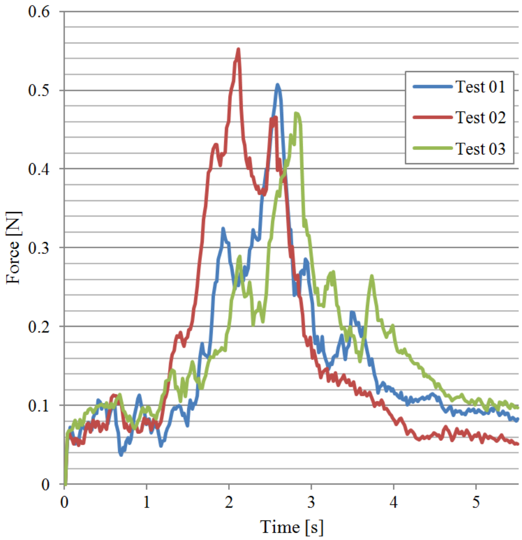


Figure 6.25: Force exerted for the same machining parameters (v = 1 mm/s, amplitude 80 μm) on Wax samples.

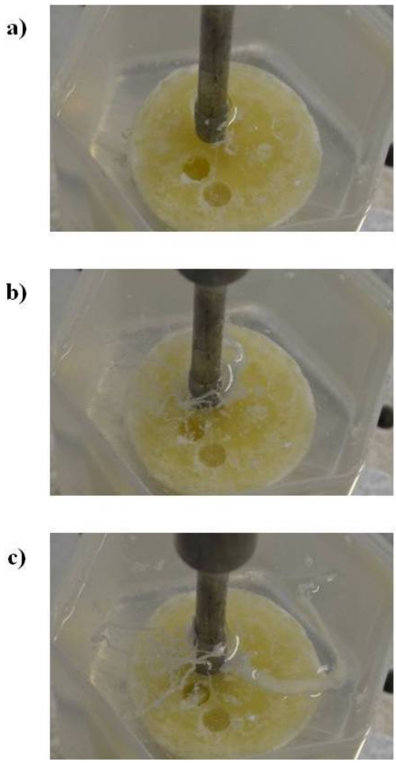


Figure 6.26: Screenshots of Wax underwater machining video.

6.4.7 Object shaping and dimensional analyses

The previous Sections analyze the use of a sonotrode for drilling operation, while the present Section aims at combining also lateral motion. An axial translation is required for the drilling operation (Figure 6.27a), while there are two more possibilities for shaping materials with the ultrasound technology: the first one is represented in Figure 1b, and consists of a longitudinal translation of the sonotrode, and it can be assimilated to a traditional milling operation. Figure 1c shows a combination of both axial and longitudinal translation, that is an operation common in the facing operation on the lathe.

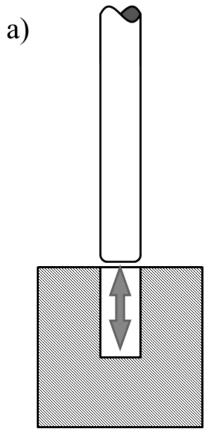
This Section explores the possibility of implementing the work procedures represented in Figure 6.27b and Figure 6.27c mounting the sonotrode on a milling machine and on a lathe. The sonotrode has been fixed on traditional machines available at the workshop of the Department of Civil and Industrial Engineering at the University of Pisa, and on a robot made available from Gruppo Scienzia Machinale.

The aim of this study is to validate the possibility of using the ultrasound technology for shaping operations of foam like materials, and specifically of polystyrene blocks. Other materials have been considered for shaping, but experiments are still ongoing at the present moment.

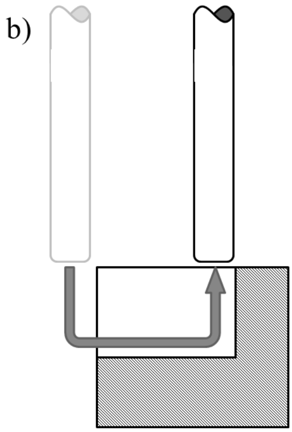
Two different setups have been created for testing the sonotrode both in milling and in turning operations. Different interfaces have been created to mount the sonotrode both on the lathe and on the robot. One more setup aimed at showing the differences between a traditional milling operation and the ultrasound milling in terms of quantity of chips created.

The sonotrode is the core of the ultrasound machining operation. The system used for experiments is the same Vibra Cell VCX 130 PB from Sonics&Materials, Inc.. The data sheet reports that the vibration frequency is constant (20 kHz), while the amplitude can be adjusted. The probe mounted on the sonotrode is an exponential one made of Titanium alloy, having a tip with a diameter of 6 mm. The sonotrode has been used at the maximum value of its amplitude for all the tests.

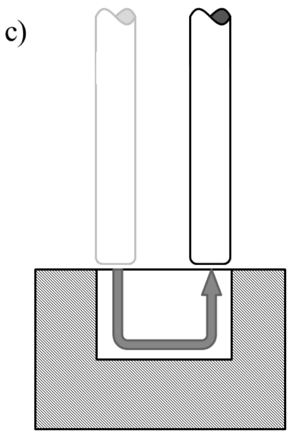
The working principle of the machining operation comprises both mechanical and thermal effects. The thermal effect is evident also from the presence of a small amount of chips generated: Figure 6.29 shows how material is deformed and where the machined material goes. The portion of material painted in blue (Figure 6.29a) is the part that is undergoing the deformation process. When machined with the sonotrode, Polystyrene softens and the blue volume of Figure 6.29a is spread on the lateral surfaces of the machined hole or groove,



(a)



(b)



(c)

Figure 6.27: The three operations that can be performed with the sonotrode: axial removal operation (a), the longitudinal removal translation (b) and their combination (c).

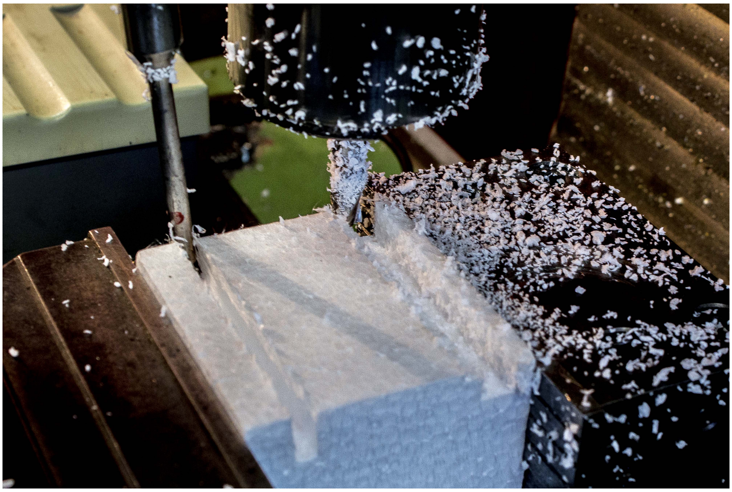


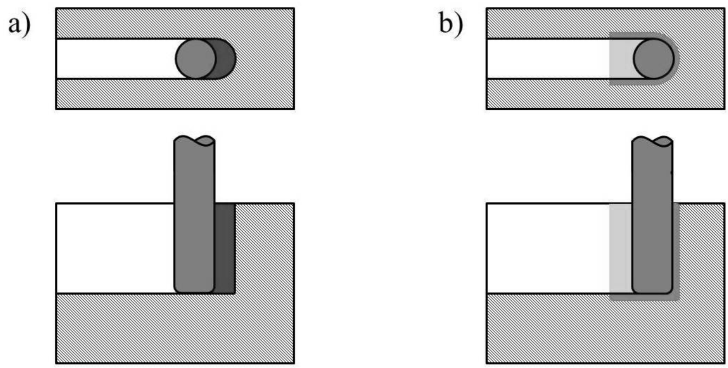
Figure 6.28: Comparison between the milling operation with the sonotrode (left) and with a traditional cutter (right).

as shown in Figure 6.29b. Not all the deformed material is spread inside the groove, so some chips and debris are generated. However, the quantity of chips generated by the sonotrode is considerably lower than the one generated by a traditional tool (see Figure 6.28).

6.4.7.1 Milling

The sonotrode was mounted on 6-axis ABB robot. The robot has been controlled in speed along the trajectories calculated with the specific software ARPP®, with a set of speeds from 5 mm/s to 20 mm/s. The software is used for the calculation of trajectories for machining operations using conventional manufacturing tools. This consideration is not trivial, since the shaping trajectory has a significant influence on the working principle of the ultrasound technology. When used as a drilling instrument, the sonotrode uses both the mechanical and thermal effect, while for the milling operations heat becomes more important. During the machining operations, the probe of the sonotrode reached 52°C, which is a significantly higher temperature if compared with the maximum one measured during the simple drilling operation (41°C).

A pyramid has been created as benchmark test for the milling operation on a polystyrene block. The initial block is approximately a parallelepiped having a square-shaped base, each side sizing 70 mm, and height 50 mm. The levels



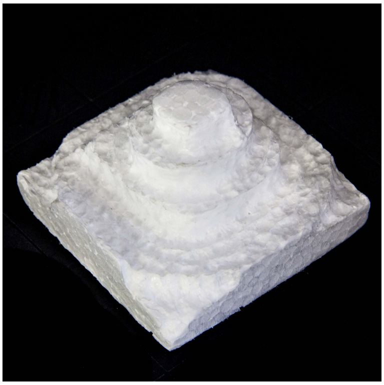
(a) (b)

Figure 6.29: The picture shows the material that is undergoing to the deformation process (a) and the same material after the machining process (b).

are alternatively circles and square shapes. The desired final surface is shown in Figure 6.30a, while the real object obtained is shown in Figure 6.30b. As mentioned above, some surfaces have a coarse precision due to the trajectories assigned by the software. Moreover it is evident how the surface quality is also affected by the working parameters, especially by the feed ratio. More detailed analysis on the surface will be discussed in Section 6.4.7.4.

One more shaping experiment was conducted on Polyurethane samples, but because of the material properties and of the high temperatures generated during the machining process, the result was not considered positive. As explained in [7], when machined in-air, the friction between the sonotrode and the workpiece generates a heat. While for drilling operations the process lasts few seconds, in the shaping of materials it can last long. In Polyurethane machining temperatures rose to 120°C, and heat became the only working principle, with Polyurethane becoming soft and deforming itself also without being in touch with the sonotrode (the softening point of Polyurethane varies significantly depending on the specific type of Polyurethane used). At the present moment there are ongoing experiments on different types of Polyurethane, especially on the Polyurethane known as Blue Foam, that is widely used in design modeling and in augmented reality [124].

(a) CAD Model

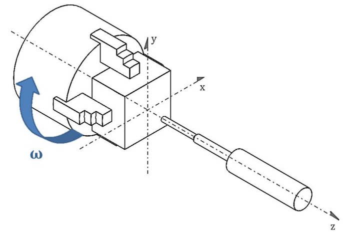


(b) Real object

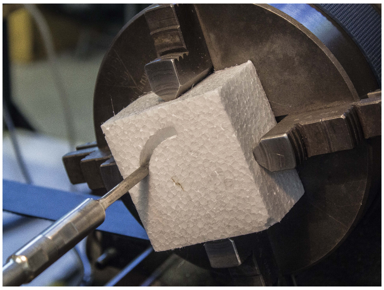
Figure 6.30: Difference between the CAD theoretical design (a) and the object shaped with the ultrasound technology (b).

6.4.7.2 Turning

In order to accomplish the turning machining operation, the sonotrode was fastened to the turret-head of the lathe. The workpiece, shaped as a prism with a constant square section of 70 mm and a height of 50 mm, was fixed to the turning machine through a combination chuck. The scheme of the setup is illustrated in Figure 6. Because of the geometry of the sonotrode and the limited excursion range of the turret head in the z-axel, only face grooving operations were possible. The shapes created in the face grooving operation on Polystyrene were circles, cylinders and spirals (Figure 6.32). The shapes created on Polyurethane samples were cylinders and spirals (Figure 6.33). The goal of the test was to evaluate the possibility of shaping material with this type of operation. The samples created on Polystyrene have been dimensionally analyzed, in order to understand the machining precision and the surface finish. Results on Polyurethane have been analyzed only at a qualitative level, since the coarse quality of results make the process unsuitable for machining on the type of Polyurethane analyzed. As for the milling process, there are ongoing experiments on different types of Polyurethane. The results of the analyses will be better explained in the Section 6.4.7.4.



(a) Scheme of the setup

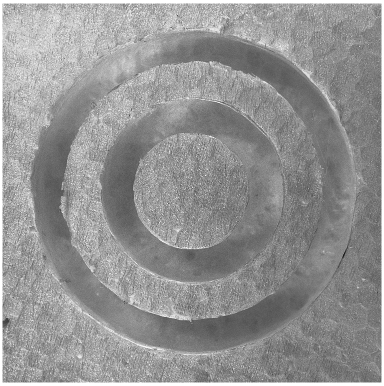


(b) Workpiece on the lathe

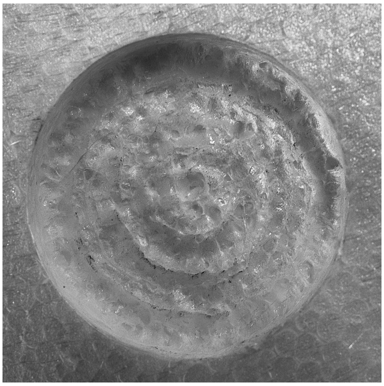
Figure 6.31: Scheme of the setup for the ultrasound machining on lathe (a) and the real setup (b). Because of the dimensions of the sonotrode, the only operation possible was the face grooving.

6.4.7.3 Optical scanner for dimensional analysis

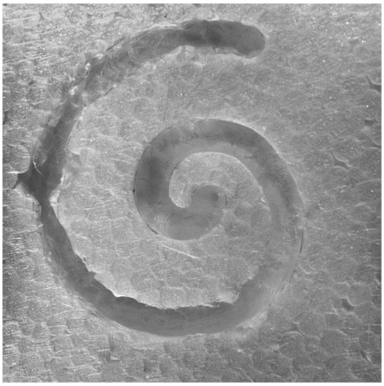
In this work, an optical scanner based on an active stereo vision approach (Figure 6.34) has been designed in order to acquire manufactured sample models [125]. A two-axis platform structure, including rotating and tilting movements, has been assembled by using two stepper motors having a resolution of 400 steps per round. The optical sensor is composed of a monochrome digital CCD camera (1,280×960 pixels) and a multimedia white light DLP projector (1,024×768 pixels). A multi-temporal Gray Code Phase Shift Profilometry (GCPSP) method is used for the 3D shape recovery. A sequence of vertical light planes is projected onto the model to be reconstructed. The planes are defined by black and white fringes with time variable period. Each acquired pixel by the camera is characterized by a light intensity that can be either bright or dark, depending on its location in the respective projected image. A binary code (0, 1 with n bit) is assigned to each pixel, where n is the number of the projected stripe patterns, and the values 0 and 1 are associated to the intensity levels, i.e. 0 = black and 1 = white. This encoding procedure provides $l = 2n - 1$ encoded lines. The 3-D coordinates of the observed scene point are then computed by intersecting the optical ray from the camera with the projected plane. The geometry of the hardware set-up, the camera ray direction and the plane equation of the corresponding stripe are known by a preliminary calibration step. The methodology provides $n_p = l_h \times l_v$ encoded points, where l_h is the horizontal resolution of the projector while l_v is the vertical resolution of the camera. The whole measurement is ob-



(a) Circles



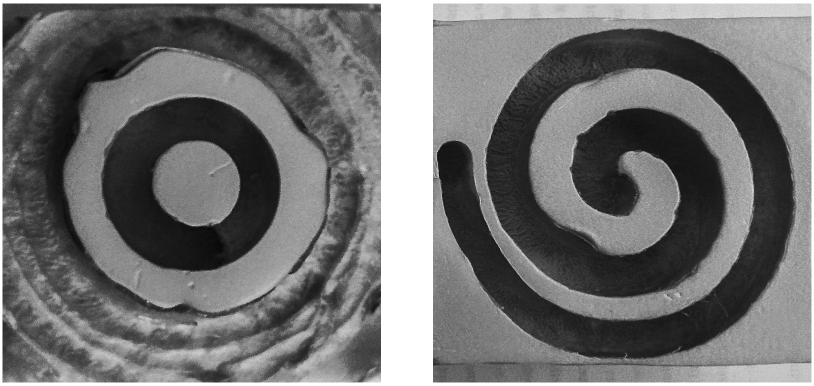
(b) Cylinder



(c) Spiral

Figure 6.32: Shapes created on Polystyrene samples.

tained by collecting 3D surface data of sample models from various directions. Different views are automatically aligned with reference to a common coordinate system on the basis of the controlled rotating axes, exploiting a calibration procedure which relate turntable positions with respect to the common reference system [126]. The combination of two distinct controlled axes allows a reliable acquisition of shape details, since different viewing directions better handle occlusion problems and undercut areas. The vision system has been configured for a working distance of 300 mm and a working volume of 100 mm×80 mm×80 mm (width×height×depth). The scanner is capable of measuring about 1 million 3D points with a spatial resolution of 0.1 mm and an overall accuracy of 0.01 mm [126].



(a) Cylinders (b) Spiral

Figure 6.33: Shapes created on Polyurethane samples.

6.4.7.4 Dimensional Analyses

Data from optical scanner have been acquired and a comparison was made based on the results of interest. Some analyses are at quantitative and qualitative level: the milled pyramid (Figure 6.30b) was analyzed to compare the overall machining quality, the milled circles (Figure 6.31a) were analyzed for evaluating the lateral precision, while the grooved cylinder (Figure 6.31b) was used for evaluating the precision of the bottom surface. Other types of analyses were only at a qualitative level, like the spiral sample both on Polystyrene and Polyurethane. The spiral (Figure 6.31c and Figure 6.32b) allows understanding how heat and speed of the sonotrode affect the quality of the surface. The rotational speed around the center of rotation O (Figure 6.35) was kept constant and was 0.5 rpm for both the samples. As in all the turning operations, the closer the tool is to the center of rotation, the lower the tangential speed is. Considering the spiral on Polystyrene, and referring to Figure 6.35 and Table6.3, it is evident that when the tangential speed decreases, the surface quality is improved. On the other hand, also the contribution of heat has to be taken into account, since when the machining operation starts, the temperature of the sonotrode is the ambient temperature, and increases during the manufacturing process. In Figure 6.35, the part of spiral from A (initial point) to C creates poor quality borders, even if the quality progressively increases while getting closer to the point C. From the point C to the final point of the machining process, the quality of the borders can be considered satisfactory.

Considering the spiral created on the Polyurethane block (Figure 6.36), it

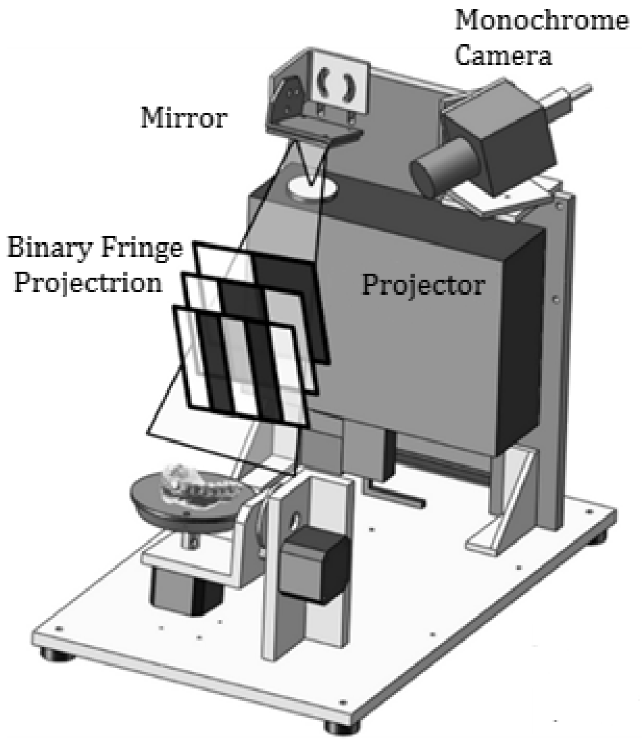


Figure 6.34: Scheme of the assembled optical dental scanner.

appears that during the initial part of the machining process (part from *A* to *B*) the quality of the machined part is good, but it gets worse in the point C. This is due to the high temperature reached by the sonotrode, which makes material melting even if it is not in contact with the sonotrode.

The comparison between the CAD model of the pyramid and the manufactured object is shown in Figure 6.37. If compared with traditional machining operations on conventional materials, the results appear to be unsatisfying. There are few considerations to take into account: the first one, and most important, is that the interface between the sonotrode may have not been connected in a tough way to the robot. This was necessary not to damage the instrument, which does not belong to the department. The second matter is the calculation of trajectories: the software used for the calculation of trajectories was set for machining operations using conventional machining tools. Furthermore, the fillet radius was not considered in the CAD model, but it was created

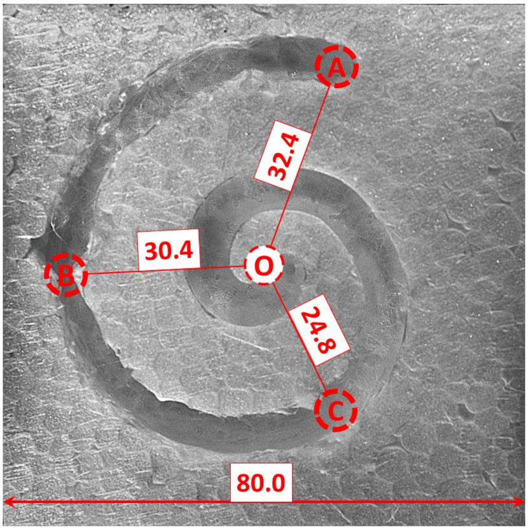


Figure 6.35: Spiral on Polystyrene block with highlighted significant points and measures [mm]: center of rotation (O), initial point (A), point where the material has been torn (B) and point from which the machining operation is satisfactory (C).

because of setting parameters for conventional machining operations.

The fillet radius has been created starting from the reverse engineering analysis, but these areas lose their importance in the comparison analysis. The last consideration regards the machined material itself, since its high level of non-homogeneity lowers the surface precision level. The percentage of measured points versus deviation values are plotted in Figure 6.38, and clearly show that the maximum precision that can be gathered is coarse. However, because of the problems explained above, more experiments with different interfaces and different trajectories have to be done before a conclusion can be made.

The circular groove shown in Figure6.32a has been used to evaluate the lateral precision of the ultrasound machining process. The comparison be-

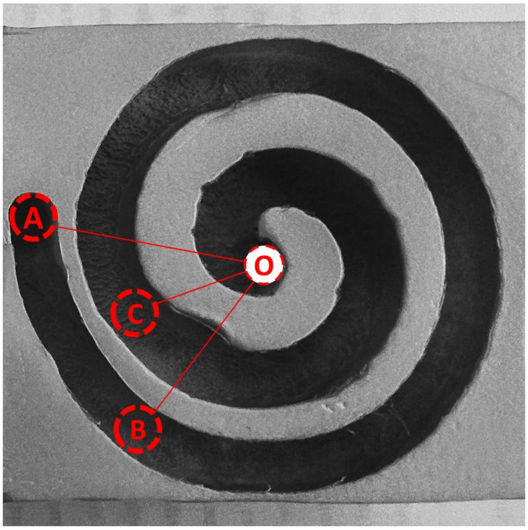


Figure 6.36: Spiral on Polyurethane block with highlighted significant points: center of rotation (O), initial point (A), point where the material starts melting even if not in contact with the sonotrode (B) and point from which the machining quality worsens (C).

Table 6.3: Measures and values of machining parameters, referring to Figure 6.35.

Point	Rotational speed [rad/s]	Distance from the Center (O) [mm]	Tangential speed [mm/s]
A	π	32.4	101.8
B	π	30.4	95.5
C	π	24.8	77.9

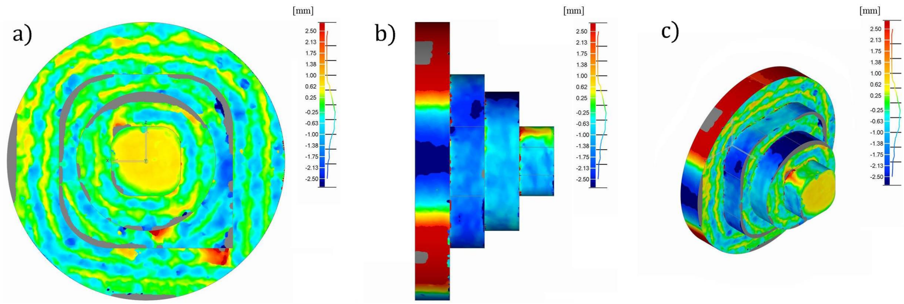


Figure 6.37: Comparison between the manufactured pyramid and the CAD model: top (a), side (b) and isometric (c) views.

tween theoretical circular surfaces and the real machined surface is shown in Figure 6.39, where a section of the specimen is analyzed. Figure 6.39 presents the deviation of the specimen from the CAD model versus percentage of points for the section shown in Figure 6.40. Compared to the results of milling operations, the number of points having a high deviation from the theoretical shape is considerably decreased. This result is considered positive at this stage of the study, but will have to be tested with different working parameters, in order to understand how they influence the shape precision.

Considering now the cylinder, the comparison between the ideal cylindrical surface and the manufactured object is used to evaluate how the working parameters, especially the feed ratio, affect the bottom surface. The results for a section of the cylinder are shown in Figure 6.41.

Figure 6.42 presents the deviation of the specimen from the CAD model versus percentage of points for the section shown in Figure 6.41. Compared to the analysis of the milled pyramid, a higher number of points has a smaller deviation from the theoretical shape, and the result can be considered encouraging at this step of the process study.

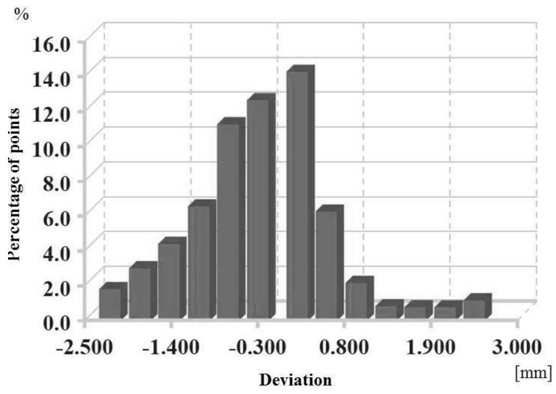


Figure 6.38: Deviation of the specimen from the CAD model versus percentage of points for the milled pyramid.

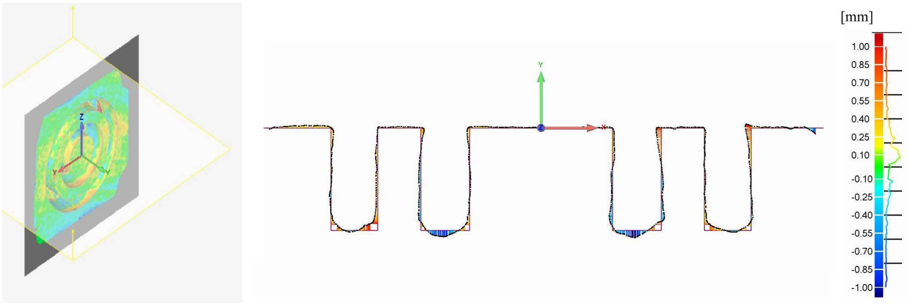


Figure 6.39: Comparison between perfectly circular surfaces and the real machined surface for the section of the specimen indicated on the left.

Figure 6.43 highlights the trajectories of the axis of the sonotrode: the blue areas refer in fact to the frontal part of the probe, while the red parts have not been properly machined. Other tests will have to be done using different working parameters, especially the feed ratio will have to be decreased in order to gather an improved bottom surface of the cylinder.

Before concluding this section, it is important to highlight how the comparative analysis values significantly vary between the shape machined with the milling manufacturing and the ones obtained using the lathe. In fact, while the deviation of the pyramid from the CAD model presents a high number of points significantly distant from their ideal position, the percentage and the maximum error decrease significantly for the lathe-machined workpieces. This allows to consider that the working parameters affected significantly the results

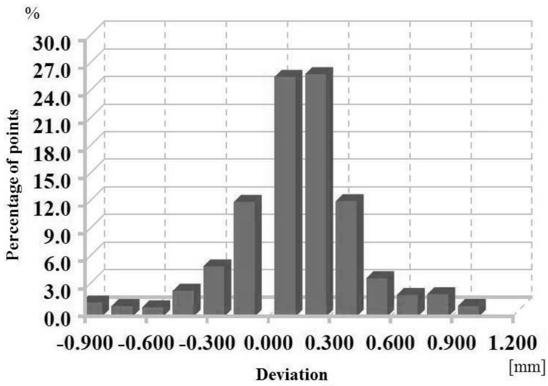


Figure 6.40: Deviation of the specimen from the CAD model versus percentage of points for the grooved circles for the section illustrated in Figure 6.39.

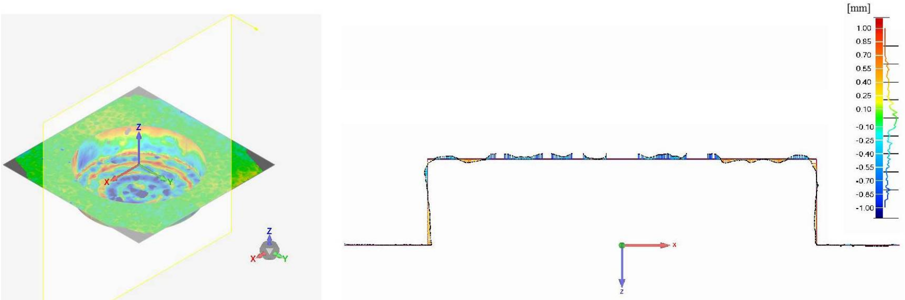


Figure 6.41: Deviation of the bottom surface of the grooved cylinder from an ideal planar surface.

of the machining process, and encourage to continue the experimental activity.

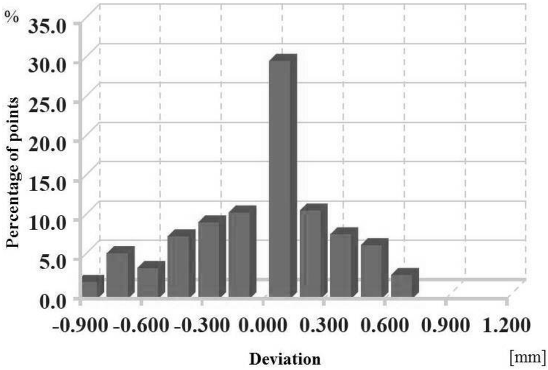


Figure 6.42: Deviation of the specimen from the CAD model versus percentage of points for the grooved cylinder for the section illustrated in Figure 6.41.

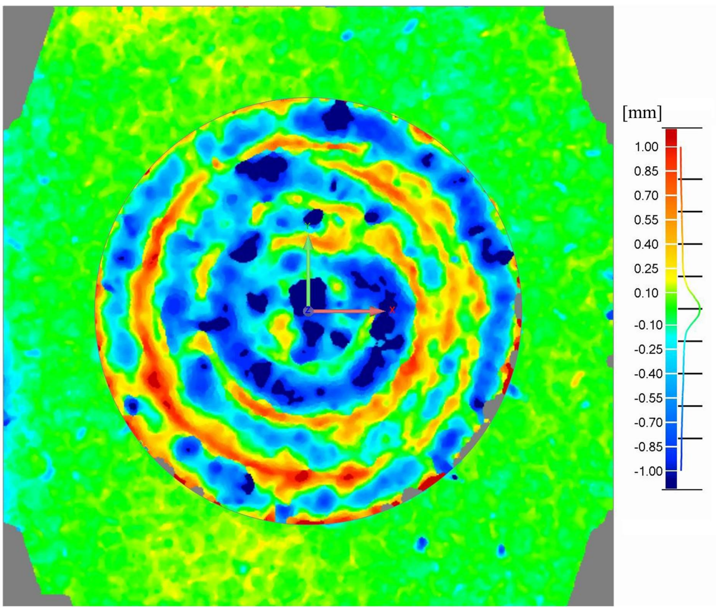


Figure 6.43: Comparison of the whole bottom surface of the grooved cylinder. The blue areas indicate where the axis of the sonotrode has passed. The deviation values are in millimeters.

6.5 Methodology for the industrial production of customized appliances

Within the orthodontic field, malocclusion problems are usually treated by using different types of appliances. In particular, Eruption Guidance Appliances (EGAs) are recommended for early orthodontic treatment or prevention of malocclusion problems. The traditional approach with EGAs is based on the use of standard prefabricated templates realized by high-pressure injection of silicon materials within metallic molds. These appliances, however, have a low degree of customization, which is usually obtained by manually adapting the mating surfaces on the specific patient. Experts in the orthodontic field believe that the customization of the EGAs would strongly enhance the results of malocclusion treatments.

EGAs, also called myofunctional devices, are removable appliances for the correction of malocclusion problems, especially recommended for early orthodontic treatment or prevention of malocclusion problems. A minimum set of different sizes and shapes is usually available on the market, and standardization is based on common anatomy of the dental arches. Thus, the choice of the particular model to be used derives from a tradeoff between the availability on the market, and the patient's anatomy. The EGA has then to be adapted on the actual shape of the arches to treat. Usually, the appliance is worn by the patient during nighttime and a few hours during daytime. It could be periodically replaced if changes and/or developments in the growth of the jaws and teeth exchange occur.

Due to the high variability between each clinical case, orthodontists believe that the creation of a customized appliance would improve the results, which are already encouraging with standard EGAs available on the market, and may allow the simultaneous correction also of other dental problems (e.g. dental misalignment). In this work, a novel approach for the design and manufacturing of EGAs is proposed. The methodology is based on the main idea that a customized device designed on the actual shape of the patient mouth instead of a standard device brings benefits in terms of more predictable outcomes and faster treatments. The main drawback that has limited till now the diffusion of customized devices has been the high cost required to manufacture a non-standard appliance, the process used for the industrial production of EGAs available on the market at the moment, and the methodology used for creating customized dental appliances in general (e.g. aligners), which employs highly skilled labor, but with processes of handicraft level. The developing of digital technologies and the reduction of costs of innovative manufacturing technologies like 3D Printing, could overcome this drawback and allow for an affordable solution.

This work presents an innovative methodology for the design and manufacturing of fully customized EGAs. The methodology is based on an extensive integration between traditional orthodontic procedures (e.g. creation of patient's dental impression, manufacturing of plaster models, wax bite registration of upper and lower arches) with advanced computer aided design processes. The methodology moves from the digitalization of the plaster models obtained by optical scanning techniques. The patient morphology is then exploited, under dental practitioner supervision, for the design of the appliance geometry through CAD modelling tools. This approach provides an accurate matching between mating surfaces of the appliance and the actual patient's dental anatomy. Medical guided assessment is required throughout the most of the data elaboration processes, in order to design the EGAs accordingly to the patient's clinical conditions. Low-pressure injection molds for the physical manufacturing of the appliances are then 3D printed using rapid prototyping techniques. The proposed methodology allows the production of patient customized appliances guaranteeing low cost manufacturing and high quality standards, similar to those typically obtained by in series productions. Moreover, the presented approach offers a high integration level with numerical and finite element methods, which can be used for both the evaluation and optimization of the forces imparted by the EGAs onto patient dental arches.

6.5.1 Background of the EGAs

Orthodontics is the branch of dentistry concerned with the study and treatment of irregular bites, and deals with the practice of manipulating patient dentition in order to provide better functionalities. Detection and correction of malocclusion problems caused by teeth irregularities and/or disproportionate jaw relationships represent the most critical aspects within an orthodontic diagnosis and treatment planning.

A survey conducted from National Health and Nutrition Examination Survey (NHANES III) in the USA revealed that a high percentage of youth needs a orthodontic treatment [127]. Focusing on malocclusion problems, even if they are more common for a certain type of ethnic groups [128], a high percentage of youth revels to have this problem. Orthodontic treatments improve both the dental health and the esthetic components [129], thus people needing to undergo a orthodontic treatment are highly encouraged to do it, even if the demand for treatment is highly influenced by many factors (e.g. cultural differences, need for orthodontic intervention, as access to care) [130, 131].

Orthodontics is continuously pushing forward the research about dental care appliances. In the last century many changes happened in medical treatment philosophy [132]: still in the 80's, a definition of traditional orthodontics was "variable-cross-section orthodontics where small wires were used for light forces and large wires for heavier ones" [133]. In recent years, non-metallic orthodontic appliances to perform non-surgical orthodontic treatments raised a growing interest. For the correction of malocclusion, treatment approaches have been thoroughly investigated in the literature. Nowadays some of them use fixed functional appliances, sometimes also highly invasive (e.g. the case presented in [134]), and some of them use removable appliances (e.g. the case studied in [135] and [136] for the Eruption Guidance Appliances (EGAs) and in [137] for the Fränkel functional regulator). In recent years, the use of non-metallic orthodontic appliances to perform non-surgical orthodontic treatments raised a growing interest.

EGAs have been introduced in the 40's [138], and the interest of industry raised in the following years, as proved by the increased number of patents like the one from Bergersen [139]. Nowadays, the Scientific Community, as well as the industrial world, is continuously studying and comparing the EGA to the other removable appliances (e.g. Janson et al. [140]). Research about the long term stability of cases treated with EGAs demonstrated that correction of malocclusion was stable [141]. Because of this reason, and because of the relatively low invasiveness of the treatment, EGA appears to be one of the most applied correction methods adopted in orthodontics in the last years.

The methodology described in the present work exploits the advantages of designing orthodontic appliances customized on the patients, thus resulting in more effective dental care treatments. Moreover, the technique proposed in this work allows the creation of high quality products, which are also economically competitive due to the decreased manufacturing costs.

6.5.2 Materials and Methods

In this section, the proposed methodology is presented and the tools used to gather the results are described. The present work aims at defining a methodology for the creation of customized appliances for malocclusion problems treatment. The design studied is based on the EGA, and it has to take into account both anatomical and functional requirements. The design process moves from the dental impression of both the upper and lower dental arches. Plaster casts are then created from dental impressions. Molds of dental arches are thus positioned with the same relative position they have in patient's mouth, taking into account both the Coronal and the Sagittal planes. Following, the model is scanned and imported in a CAD software for surface elaboration. Once the final relative position of arches is fixed, two alternatives are possible: the direct printing of the appliance through an Additive Manufacturing (AM) technique, or the printing, still using the AM technique, of the mold for the creation of the appliance through injection of silicone. This work considers only the possibility of manufacturing the EGA through the creation of a mold. The overall procedure can be summarized in the following steps:

1. creation of the dental molds
2. 3D virtual model
3. virtual design of the mold
4. production and testing of the appliance

All these steps, schematically represented in Figure 6.44, are described more in detail in the following subsections. This work focuses on the last three steps, since they are the ones who involve more considerably the engineering contribution to the work.

6.5.2.1 Creation of the dental molds

The first step of the methodology work flow is the acquisition of dental impression of the patient and the creation of dental molds. This is a preliminary activity for the creation of customized dental appliances, and it is based on traditional orthodontics operations. The orthodontist takes the dental impression using a traditional kit (e.g. the one shown in [142]), then he creates the plaster casts. Once plaster casts are created from the dental impressions, dental arches are aligned into the real case position thanks to the impression of the bite over a wax wafer or other devices (e.g. the ones described in [143]), specifically designed for precise bite registration. Plaster casts are then fixed to the position by external supports (e.g. rubber bands and clamps) for the subsequent surface acquisition phase. This is the only traditional step proposed in this methodology.

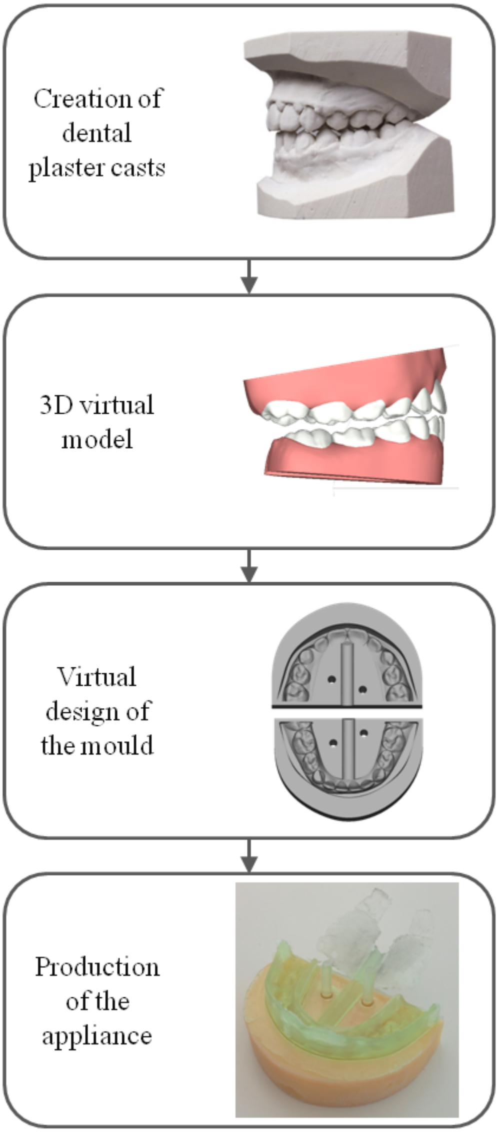


Figure 6.44: Flowchart of the proposed methodology.

6.5.2.2 3D virtual model

At this step, aligned plaster casts generated during the previous stage are now used for the creation of a virtual model. The block containing the plaster casts, the supports and the wax wafer is inserted in a system for the acquisition of a 3D cloud of points, in order to recreate the surface of dental arches. The creation of the 3D virtual model is divided into four sub-phases, which are:

- image acquisition
- data elaboration and refinement of the surfaces
- segmentation
- medical guided assessment

Each step is described in detail in the following sections, and the equipment used for the test of the procedure is described finally in the case study section.

Image acquisition This sub-step is the first one toward the digitalization of the model. The plaster casts are positioned in a device for surface acquisition. For this work a 3D scanner has been taken into account, even though other surface acquisition methods are possible [144] specifically for plaster cast or other uses still related to the orthodontic field [145, 146]. For the 3D scanner acquisition phase, three substeps are necessary:

scanning of aligned arches: allows to gather information about the relative position of the dental arches. This step does not create inner surfaces of plaster casts

removal of support elements: is an intermediate step, which permit to scan the single dental arches for acquiring information about inner surfaces

scanning of upper and lower dental arches when each plaster cast is scanned singularly, all the surfaces of interest are accessible to the scanning system.

Therefore three scans are required, one for each dental arch, and one for relative positioning of dental arches. The three scans are required to overcome some problems due to the typology of surface acquisition method system adopted.

Data elaboration and refinement of the surfaces Surfaces acquired contain both the dental arches and surfaces extraneous to the patient's dental profile. For instance the surfaces of rubber bands are included in the clouds of points of the aligned arches, but have to be removed for the analysis of data and for the surface elaboration process. Furthermore, the scanning system does not allow to gather information of the totality of the dental arches at once from the scanning of aligned arches, since when plaster casts are aligned, the inner surfaces are hidden from the outer surfaces. This problem is solved by scanning also each plaster cast standing alone, thus aligning the surfaces acquired according to the cloud of points generated by the aligned arches scanning. Once points are acquired, they undergo a refinement process, which consists of noise reduction, removing of unnecessary points, creation of borders and sampling of points according to the curvature of the surface. The most the surface is complex, the highest the density of points is. The following step is the alignment of the clouds of the dental arches with the cloud of the general byte scanning. Once the operation is concluded, the cloud generated from the scanning of the in-position dental arches is deleted, and surfaces of upper and lower plaster casts are created from the clouds of points. The software used for the operations described in this step is Geomagic Studio®.

Segmentation Since the methodology could be used also for the realignment of single teeth, an individual tooth segmentation process is required [147]. In case of children treatment with EGAs, the segmentation process considers only the division between teeth and gingiva. In this case, the surfaces of visible dentition structures (tooth crowns) and oral soft tissues are created from the optical scanning process onto patient's dental plaster casts. The overall surface representing tooth shapes and oral soft tissue is then segmented into disconnected regions, representing the individual crown geometries and the gingiva through a semi-automated procedure, which exploits the curvature of the digital mouth model. Since teeth are separated from the gingiva, they can be moved to different position, without altering the main structure of dental arches.

In case of adult treatment, other more accurate procedures can be used for digital reconstruction of the patient's anatomical tissues involved in an orthodontic treatment, by integrating two different imaging techniques: CBCT scanning and surface structured light scanning [126]. The combination of the two techniques allow to reconstruct tooth roots and bone tissues by processing CBCT data sets on the basis of an active contour model in a level set formulation [125].

Medical guided assessment Based on dentist's prescription, the 3D model is manipulated using an apposite software. In particular, the realignment of teeth (Figure 6.45) is possible thanks to the segmentation phase, which guarantees teeth separated from the gingiva. Since the material of the EGA is soft if compared to traditional aligners, the experts believe that the realignment can be efficient for few teeth, in particular the central, lateral and cuspid ones. For what concerning the malocclusion treatment, dental arches can be moved from the original position (Figure 6.45a) to a different one (Figure 6.45b). Also, depending on the type of malocclusion, i.e. malocclusion type I, type II or type III [128], the EGA has to provide a relative position of dental arches that is not the final desired one, but has a different condition (Figure 6.45c), that allows to correct the malocclusion accordingly to the specific case.

Both the realignment of teeth (Figure 6.46) and repositioning of dental arches can be done in one single step, or can be divided in more substeps, accordingly to dentist's prescription. This subdivision depends on the severity of the orthodontic treatment, and on the specific patient's anatomical conditions.

6.5.2.3 Virtual design of the mold

The design of the mold has to take into account the problematic connected to manufacturing processes of the mold itself, and to the creation of the appliance. In particular, since the procedure adopted for the creation of the EGA is low pressure injection, the main requirement is the possibility of extracting the final product from the mold. Thus, the division plane and the presence of undercuts have to be carefully considered, accordingly to the creation of molds for traditional injection operation procedures [148].

For what regards the manufacturing process of the mold, two main possibilities can be taken into account: the creation of a set of interchangeable fixed

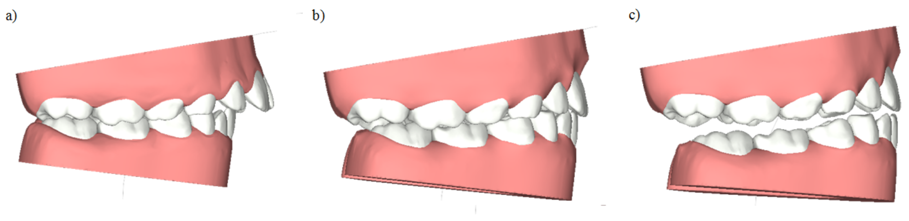


Figure 6.45: Malocclusion correction steps: (a) initial position, (b) final desired position and (c) relative position for correction of malocclusion problems dependently on the malocclusion problem (i.e. class I, class II or class III).

and standardized molds, among which adapting the dental arches of the patient, and the creation of totally customized molds out from rapid prototyping techniques. The first methodology implies a higher initial investment due to the construction of the standard molds that have to be created using metal alloys in order to resist to the production of a high number of appliance. On the other hand, this procedure allows the manufacturing of high quantity appliances, reducing the quantity of customized material to be installed in the mold, thus reducing the timing and the cost of Rapid Prototyping material and machine use. The second methodology, also studied by Salmi et al. [149], is more indicated for low quantity production series, since it is based on totally customized molds, that have to be manufactured from rapid prototyping techniques. In this case, the mold is created using additive manufacturing procedures, already divided in two or more parts to avoid undercuts and to allow the extraction of the appliance. Reference elements have to be included to allow the correct relative positioning of the components of the mold.

For this work, the second option was used, since it is the one that allows the creation of prototypes with a low initial investment, thus allowing the creation of prototypes to be tested before the eventual production of the appliance. For the external surfaces of the EGA, it is possible to choose among a wide variety of shapes.

One of the advantages of the methodology described in this work, is the possibility of simulating, through a FEM analysis, the stress that is applied to the EGA, thus allowing to eventually reinforce the appliance before its creation and before manufacturing the mold. This is also depending on the type of

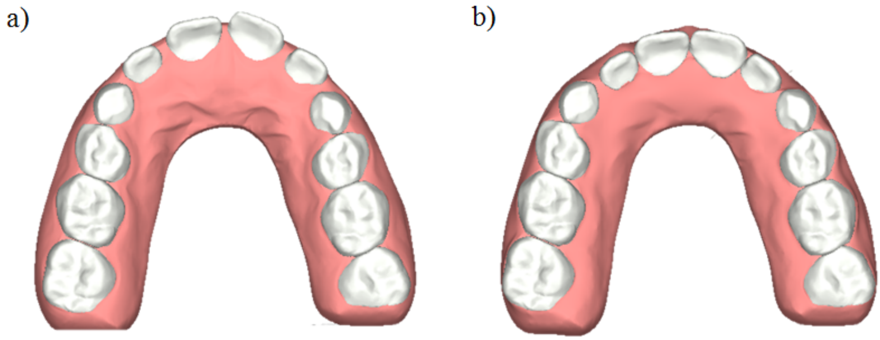


Figure 6.46: Realignment of teeth accordingly to medical prescriptions: (a) the initial condition and (b) the final alignment of teeth.

treatment suggested, on its severity and on the design of the EGA, since the outer surfaces can be designed in many different ways. An example of the stress analysis performed on a preferred design of the EGA is illustrated in Figure 6.47.

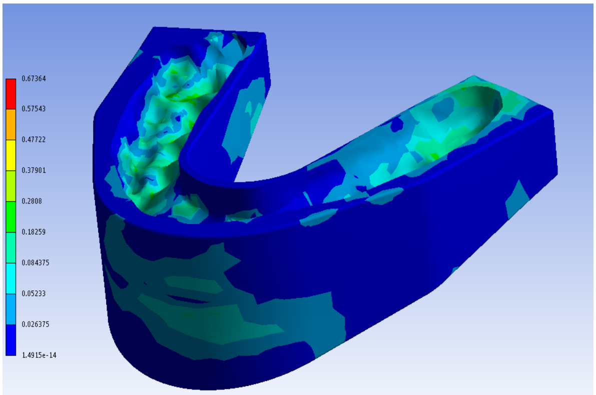


Figure 6.47: An example of FEM analysis that can be performed on customized appliances before its manufacturing.

6.5.2.4 Production of the appliance

The appliance was manufactured interfacing the mold created with an AM machine with a low pressure injection system. Silicon was injected into a system that included the mold of the EGA into a plaster block, as shown in Figure 6.48a. The system ready for silicon injection is shown in Figure 6.48b. Among the possible alternatives for AM, also explored in [150], the selected one was the Fused Deposition Manufacturing (FDM). If compared to other AM techniques [14], FDM main drawback is the limited extension of the workspace. On the other hand, its main advantages are the wide variety of materials that can be used, the good precision quality and, even if it is not the best among the AM techniques, the resolution of the surface created. Furthermore, surface finishing can be improved setting adequate extrusion parameters [151], or using chemical solutions to smoothen the irregularities due to the staircase effect [152].

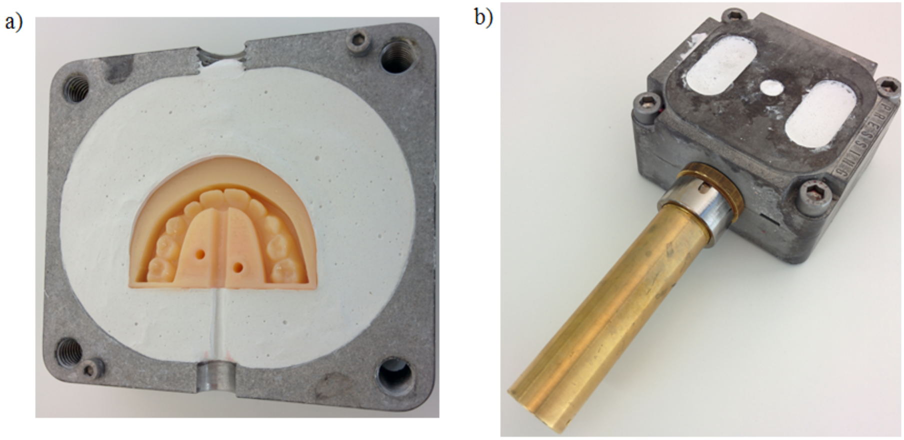


Figure 6.48: (a) the mold of the EGA in the plaster block and (b) the system ready for injection.

6.5.3 Case Study

Based on a clinical case, a case study of EGA was manufactured. For the acquisition of the images a plaster casts provided by orthodontists, together with the wax wafer for registration were used.

The 3D acquisition system used was specifically developed with the aim at digitizing the plaster casts in their original misaligned position (Figure 6.49). The system is composed of the a 8-bit monochrome CCD digital camera (The Imaging Source DMK 41BF02, resolution 1280×960 pixels), equipped with a 16 mm focal length lens (PENTAX, C31634KP 2/3" C-mount), and a multimedia white light DLP projector (OPTOMA EX330e, resolution XGA 1024×768 pixels).

The 3D shape recovery uses a multi-temporal Gray Code Phase Shift Profilometry (GCPSP) method, projecting a sequence of black and white vertical fringes. The working volume of the acquisition system is of 100 mm×80 mm×80 mm (width×height×depth), with a spatial resolution of 0.1 mm and an overall accuracy of 0.01 mm [126].

Dental arches have been acquired accordingly to the procedure described in the Image acquisition section, and the plaster casts aligned in the original position are shown in Figure 6.50a, while Figure 6.50b shows the plaster casts of dental arches used for acquiring the totality of the surfaces (inner and outer surfaces).

Final digital reproductions of patient's dental structures and of the den-

Figure 6.49: The scanner used for the surface acquisition of dental arches.

tal arches alignment are obtained by merging different range maps within an automatic multi-view scanning process, then are merged together to recreate the dental patient's conditions. After this step, the cloud of points is post-processed reducing the noise created during the acquisition phase and reducing the number of points. The final file of the surface points, prior its conversion to surface entities is shown in Figure 6.51.

Once surfaces have been created and the segmentation process has been applied, dividing teeth from the gingiva. Under medical assessment, the relative position of dental arches have been corrected, accordingly also to the malocclusion problem type (Figure 6.45). In this case study, also teeth misalignment was corrected (Figure 6.46).

The mold was designed using a CAD software for the creation of the outer surfaces. Boolean operations have been used both for creating the dental impression in the EGA, and for creating the negative of the EGA for the design of the mold. The mold was designed to be interfaceable with a commercially available low pressure injection system, in this case the J-100 Evolution®from Pressing Dental S.r.l.. The rapid prototyping technology used for the creation of the mold was the fused deposition manufacturing, and the machine used in this case study was the Object Eden500V 3D Printer®from Stratasys, Inc..

The 3D model of the mold and the rapid manufactured appliance are shown respectively in Figure 6.52a and Figure 6.52b. The surface finishing is different between the surfaces of the mold that interface with the EGA, and the other areas of the rapid prototyped component, due to the effects of the post-treatment used to improve the EGA's roughness. The rapid prototyped mold is shown prior to its insertion into the low pressure injection system shown in Figure 6.48. The appliance before its extraction from the mold is shown in Figure 6.53.

6.6 Conclusions

In this Chapter are exposed some way to solve the problematics already highlighted both in Chapter 5 and in Section 6.2. It is not the objective of this thesis to solve all the problems that can be encountered in the prototyping phase, since it would be impossible. It is more in the intention of the candidate to show how the prototyping phase, even if presenting some problems, still represents a big opportunity for the inventor.

a)

b)

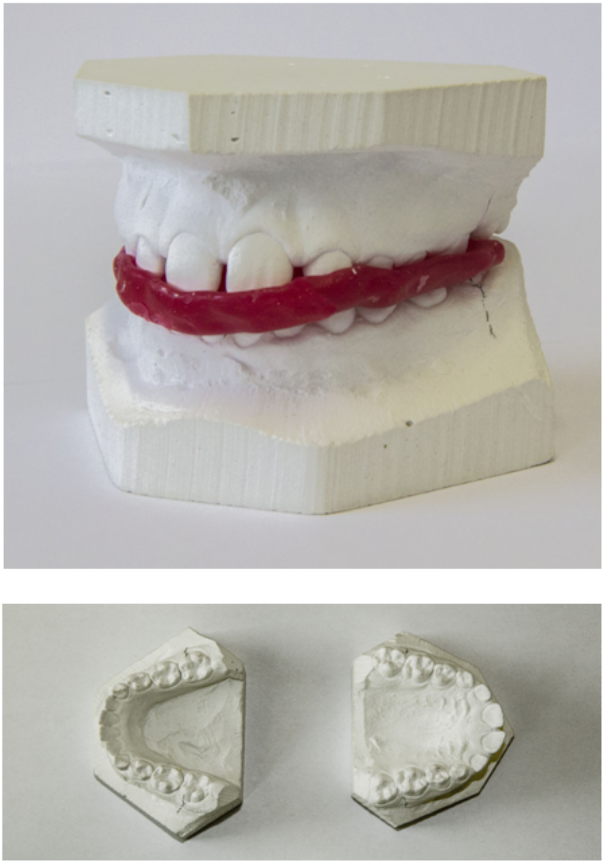


Figure 6.50: (a) Plaster casts of the dental arches aligned in the initial position and (b) dental arches. In (a) it is visible the wax wafer (in red) used for the registration of dental arches.

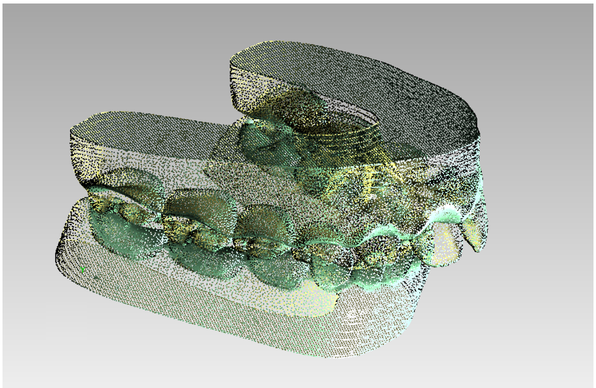


Figure 6.51: The cloud of points obtained once the surface of the single plaster casts are merged together.

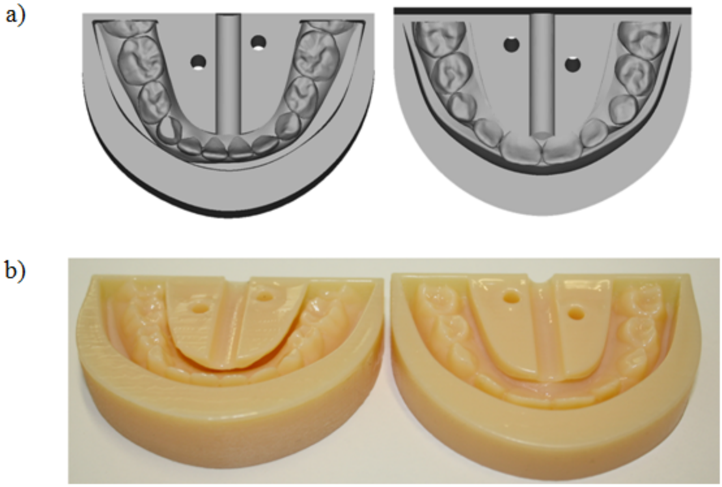


Figure 6.52: Virtual design of the mold and (b) the mold created with AM techniques.

Figure 6.53: The appliance before the extraction from the mold created with rapid prototyping techniques.

This Chapter was partially based on the following publications:

- J Tilli, G Fantoni, L Jaquemetton, and DL Bourell. Improving mechanical properties of laser sintered nylon-12. *AITeM* 2015 *submitted*, 2015. [6]
- G Fantoni, J Tilli, FAWeilemann Belo, and R Ishak. Rapid manufacturing of foam-like materials through the use of sonotrode: an overview. *Proceedings of the 2014 International Conference on Innovative Design and Manufacturing*, pages 233–238, 2014. [7]
- J Tilli, G Fantoni, and S Currenti. Underwater drilling operations of foam like materials and wax using the ultrasound technology. *Proceedings of the 2014 International Conference on Innovative Design and Manufacturing*, pages 155–160, 2014. [8]
- J Tilli, G Fantoni, S Currenti, and AV Razionale. Object shaping of polystyrene with a sonotrode. *Proceedings of the 25th Solid Freeform Fabrication Symposium*, pages 95–109, 2014. [9]
- J Tilli, A Paoli, AV Razionale, and S Barone. A novel methodology for the creation of customized eruption guidance appliances. *ASME* 2015 *submitted*, 2015. [10]
- G Fantoni, and J Tilli. Dispositivo e metodo per lavorazione ad ultrasuoni. *Italian Patent Application No. PI 2014 A000055*. [153]

Chapter 7

Conclusion

The thesis analyzed many steps of the concept design, especially the ones more related to the prototyping phase. One of the main limitation of the work presented in the previous Chapters is the attempt to analyze not the development of a single product from its design to the final prototyping, but the will to face vertically many different procedures for each step of the prototyping phase.

The opinion of the candidate is that it is more valuable to illustrate more activity and more different ways to face a problem, obviously connected to the projects covered during the PhD, rather than focusing on the development of a single asset with a unique way of dealing with the problem of prototyping.

This is the reason for which the flowchart of the concept design phase has been expanded and treated in different ways according to the needs of each single project: design problems have been presented and faced in order to structure this important step of the concept design, and to expand the potential of the one who is facing the development phase of a new product or service.

The one who is developing a new product is also facing the problem of which is the concept with the highest potential, so on which idea it is worth investing time and resources. This phase can vary significantly depending on the type of product or service, which are the inputs (e.g. comparing existing products to new concepts) and which are the expected outputs. Does the user want a ranking of concepts, or does he want information in order to choose accordingly to his experience? Does he want a selection method or does he want a table reporting the properties of the concept? It would have been impossible to face all these problematics with a single case study, and this is the reason for why it has been decided to report the selection processes adopted in more activities carried out during the PhD.

Some of the projects developed during the course of the PhD were also presented in order to highlight which were the problems faced, and to illustrate how the design concept methods could be applied to practical cases. Some possible ways to solve the problematics of these projects have been presented, and it is obvious that different projects would have presented different difficulties, but they can be used for solving analog problems, like the improvement of mechanical properties of components manufactured using rapid prototyping techniques, or the development of flexible and cheap manufacturing processes. For what concerns the development of the ultrasound manufacturing process, it is also interesting to see how the design by analogy can be applied also to methods, since that the process was designed for the realization and the shaping of polystyrene blocks for the surf industry, but it has successfully been applied for the realization of components for pretotypes and prototypes. Finally, with the development of a methodology for the production series of customized appliances for orthodontic use, it was found what is the ring junction between the prototyping for the industry (i.e. creation of prototypes having the same properties of the final product) and prototyping for research (i.e. creation of unique objects), with a look to those which are the subsequent stages of production.

Bibliography

[1] A Savoia. Pretotype it-make sure you are building the right it before you build it right, 2011.

[2] KT Ulrich, SD Eppinger, and A Goyal. *Product design and development*, volume 2. McGraw-Hill New York, 2011.

[3] G Fantoni, D Gabelloni, and J Tilli. Concept design of new grippers using abstraction and analogy. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 227(10):1521–1532, 2013.

[4] G Fantoni, S Capiferri, and J Tilli. Method for supporting the selection of robot grippers. *Procedia CIRP*, 21:330–335, 2014.

[5] J Tilli, A Brando, and G Fantoni. Gripping device for heavy and deformable materials handling: Concept, design, selection and test. *Procedia CIRP*, 21:373–378, 2014.

[6] J Tilli, G Fantoni, L Jaquemetton, and DL Bourell. Improving mechanical properties of laser sintered nylon-12. *AITeM 2015* submitted, 2015.

[7] G Fantoni, J Tilli, FA Weilemann Belo, and R Ishak. Rapid manufacturing of foam-like materials through the use of sonotrode: an overview. *Proceedings of the 2014 International Conference on Innovative Design and Manufacturing*, pages 233–238, 2014.

[8] J Tilli, G Fantoni, and S Currenti. Underwater drilling operations of foam like materials and wax using the ultrasound technology. *Proceedings of the 2014 International Conference on Innovative Design and Manufacturing*, pages 155–160, 2014.

[9] J Tilli, G Fantoni, S Currenti, and AV Razionale. Object shaping of polystyrene with a sonotrode. *Proceedings of the 25th Solid Freeform Fabrication Symposium*, pages 95–109, 2014.

[10] J Tilli, A Paoli, AV Razionale, and S Barone. A novel methodology for the creation of customized eruption guidance appliances. *ASME 2015* submitted, 2015.

[11] MP Groover. *Fundamentals of modern manufacturing: materials processes, and systems*. John Wiley & Sons, 2007.

[12] M Santochi and F Giusti. *Tecnologia meccanica e studi di fabbricazione*. Casa Editrice Ambrosiana, 2000.

[13] C Sommer. *Non-traditional machining handbook*. Advanced Publishing, Inc, 6950 Fulton Street, Houston, TX 77022, USA, 2000.

[14] DT Pham and RS Gault. A comparison of rapid prototyping technologies. *International Journal of Machine Tools and Manufacture*, 38(10-11):1257–1287, 1998.

[15] RobLog (Robotic Logistics). `http://www.roblog.eu/`. Accessed: 2015-01-20.

[16] G Fantoni, C Taviani, and R Santoro. Design by functional synonyms and antonyms: a structured creative technique based on functional analysis. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 221(4):673–683, 2007.

[17] JS Linsey, KL Wood, and AB Markman. Increasing innovation: presentation and evaluation of the wordtree design-by-analogy method. In *ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 21–32. American Society of Mechanical Engineers, 2008.

[18] D McAdams and K Wood. Quantitative measures for design by analogy. In *Proc. ASME Design Theory and Methodology Conference, DETC2000/DTM-14562*, 2000.

[19] GS Altshuller. Creativity as an exact science: The theory of the solution of inventive problems. 1984. *Gordon & Breach Science Publishing, New York*, 1984.

[20] JKS Nagel, RL Nagel, RB Stone, and DA McAdams. Function-based, biologically inspired concept generation. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 24(04):521–535, 2010.

[21] BT Christensen and CD Schunn. The relationship of analogical distance to analogical function and preinventive structure: The case of engineering design. *Memory & cognition*, 35(1):29–38, 2007.

[22] CM Eckert, M Stacey, and C Earl. References to past designs. *Studying designers*, 5(2005):3–21, 2005.

[23] JFV Vincent and DL Mann. Systematic technology transfer from biology to engineering. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, 360(1791):159–173, 2002.

[24] B Andrea, F Gualtiero, et al. Expanding the functional ontology in conceptual design. *Guidelines for a Decision Support Method Adapted to NPD Processes*, 2007.

[25] Y Bar-Cohen. Biomimetics—using nature to inspire human innovation. *Bioinspiration & Biomimetics*, 1(1):P1, 2006.

[26] G Pahl, W Beitz, J Feldhusen, and KH Grote. *Engineering design: a systematic approach*, volume 157. Springer, 2007.

[27] KT Ulrich. *Product design and development*. Tata McGraw-Hill Education, 2003.

[28] B Hyman. Fundamentals of engineering design. *Upper Saddle River, NJ: Prenice-Hall*, 1998.

[29] LH Shu, RB Stone, DA McAdams, JL Greer, et al. Integrating function-based and biomimetic design for automatic concept generation. *Guidelines for a Decision Support Method Adapted to NPD Processes*, 2007.

[30] A Chakrabarti, P Sarkar, B Leelavathamma, and BS Nataraju. A functional representation for aiding biomimetic and artificial inspiration of new ideas. *AIE EDAM*, 19(02):113–132, 2005.

[31] I Kato and K Sadamoto. *Mechanical hands illustrated*. Taylor & Francis, Inc., 1986.

[32] S Kim, M Spenko, S Trujillo, B Heyneman, V Mattoli, and MR Cutkosky. Whole body adhesion: hierarchical, directional and distributed control of adhesive forces for a climbing robot. In *Robotics and Automation, 2007 IEEE International Conference on*, pages 1268–1273. IEEE, 2007.

[33] AF Van der Merwe and S Matope. The physical design of micro-grippers actuated by van der waals forces for use in micro-material handling. In *23rd Annual SAIIE Conference Proceedings*, page 178, 2009.

[34] J Hirtz, RB Stone, DA McAdams, S Szykman, and KL Wood. A functional basis for engineering design: reconciling and evolving previous efforts. *Research in engineering Design*, 13(2):65–82, 2002.

[35] E Novitskaya. Transformation of structurally similar elements of technical system. *Proceedings of the European TRIZ association, TRIZ future 2003*, 2003.

[36] G Voland. *Engineering by design*. Pearson Education India, 1999.

[37] DG Ullman. *The mechanical design process*, volume 2. McGraw-Hill New York, 1992.

[38] V Hubka, MM Andreasen, W Ernst Eder, and PJ Hills. *Practical studies in systematic design*. Butterworths London etc., 1988.

[39] K Otto and KL Wood. *Product design: techniques in reverse engineering and new product development*. Prentice Hall, Upper Saddle River, 2003.

[40] JS Gero and U Kannengiesser. *Product design: techniques in reverse engineering and new product development*. Kluwer Academic Publishers, 2003.

[41] LD Miles. Value analysis and engineering, 1962.

[42] JA Collins, BT Hagan, and HM Bratt. The failure-experience matrix—a useful design tool. *Journal of Manufacturing Science and Engineering*, 98(3):1074–1079, 1976.

[43] S Szykman, JW Racz, and RD Sriram. The representation of function in computer-based design. In *Proceedings of the 1999 ASME design engineering technical conferences (11th international conference on design theory and methodology)*, 1999.

[44] A Little, K Wood, and D McAdams. Functional analysis: A fundamental empirical study for reverse engineering, benchmarking and redesign. In *Proceedings of the 1997 Design Engineering Technical Conferences*, volume 97, 1997.

[45] RB Stone and KL Wood. Development of a functional basis for design. *Journal of Mechanical Design*, 122(4):359–370, 2000.

[46] D Gabelloni, R Apreda, G Fantoni, et al. On the link between features and functions. In *DS 68-2: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 2: Design Theory and Research Methodology, Lyngby/Copenhagen, Denmark, 15.-19.08. 2011*, 2011.

[47] MS Hundal. *Systematic mechanical designing: a cost and management perspective*. ASME Press New York, NY, 1997.

[48] C Blanes, M Mellado, C Ortiz, and A Valera. Review. technologies for robot grippers in pick and place operations for fresh fruits and vegetables. *Spanish Journal of Agricultural Research*, 9(4):1130–1141, 2011.

[49] G Fantoni and M Porta. A critical review of releasing strategies in microparts handling. In *Micro-Assembly Technologies and Applications*, pages 223–234. Springer, 2008.

[50] GJ Monkman, S Hesse, R Steinmann, and H Schunk. *Robot grippers*. John Wiley & Sons, 2007.

[51] Database of grippers designed by analogy. `http://www.centropiaggio.unipi.it/sites/default/files/`. Accessed: 2015-01-20.

[52] M Tichem, D Lang, and B Karpuschewski. A classification scheme for quantitative analysis of micro-grip principles. *Assembly automation*, 24(1):88–93, 2004.

[53] TB Gjerstad, TK Lien, and JO Buljo. Handle of non-rigid products using a compact needle gripper. In *39th CIRP international seminar on manufacturing systems*, 2006.

[54] H Kazerooni and C Foley. A robotic mechanism for grasping sacks. *Automation Science and Engineering, IEEE Transactions on*, 2(2):111–120, 2005.

[55] A Kirchheim, M Burwinkel, and W Echelmeyer. Automatic unloading of heavy sacks from containers. In *Automation and Logistics, 2008. ICAL 2008. IEEE International Conference on*, pages 946–951. IEEE, 2008.

[56] G Fantoni, M Santochi, G Dini, K Tracht, B Scholz-Reiter, J Fleischer, TK Lien, G Seliger, G Reinhart, J Franke, et al. Grasping devices and methods in automated production processes. *CIRP Annals-Manufacturing Technology*, 63(2):679–701, 2014.

[57] GH Tzeng and JJ Huang. *Multiple attribute decision making: methods and applications*. CRC Press, 2011.

[58] F Franceschini. *Advanced quality function deployment*. CRC Press, 2001.

[59] G Seliger, F Szimmat, J Niemeier, and J Stephan. Automated handling of non-rigid parts. *CIRP Annals-Manufacturing Technology*, 52(1):21–24, 2003.

[60] VP Agrawal, A Verma, and S Agarwal. Computer-aided evaluation and selection of optimum grippers. *The International Journal Of Production Research*, 30(11):2713–2732, 1992.

[61] PP Bhangale, VP Agrawal, and SK Saha. Attribute based specification, comparison and selection of a robot. *Mechanism and Machine Theory*, 39(12):1345–1366, 2004.

[62] CL Hwang and K Yoon. Multiple attribute decision making: Methods and applications, a state of the art survey. *Sprinnger-Verlag, New York, NY*, 1981.

[63] F Montagna. Decision-aiding tools in innovative product development contexts. *Research in Engineering Design*, 22(2):63–86, 2011.

[64] G Boothroyd and P Dewhurst. *Product design for assembly*. Boothroyd Dewhurst Incorporated, 1987.

[65] CL Pasquire and GE Connolly. Design for manufacture and assembly. In *11th Annual Conference of the International Group for Lean Construction*, pages 184–94, 2003.

[66] MM Andreasen, S Kähler, and T Lund. *Design for assembly*. Ifs Publications London, 1983.

[67] GQ Huang. *Design for X: concurrent engineering imperatives*. Springer, 1996.

[68] F Failli and G Dini. Neural-based grasping for industrial grippers. In *Proceedings of the 33rd International MATADOR Conference*, pages 81–86. Springer, 2000.

[69] KNG Fuller and DFRS Tabor. The effect of surface roughness on the adhesion of elastic solids. *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*, 345(1642):327–342, 1975.

[70] P Lambert, V Vandaele, and A Delchambre. Non-contact handling in micro-assembly: state of the art. In *Actes papier de l'International Precision Assembly Seminar*, pages 67–76, 2004.

[71] H Van Brussel, J Peirs, D Reynaerts, A Delchambre, G Reinhart, N Roth, M Weck, and E Zussman. Assembly of microsystems. *CIRP Annals-Manufacturing Technology*, 49(2):451–472, 2000.

[72] EMR Ruprecht. *Prozesskette zur Herstellung schichtbasierter Systeme mit integrierten Kavitäten*. Shaker, 2012.

[73] J Fleischer, A Ochs, and F Förster. Gripping technology for carbon fibre material. In *CIRP International conference on competitive manufacturing: Green manufacturing for a blue planet*, pages 65–71, 2013.

[74] M Carello, C Ferraresi, and C Visconte. A new flexible pneumatic finger for a fruit-harvesting hand. *7th International Symposium on Fluid Control, Measurement and Visualization*, 2003.

[75] S Kim, C Laschi, and B Trimmer. Soft robotics: a bioinspired evolution in robotics. *Trends in biotechnology*, 31(5):287–294, 2013.

[76] R Deimel and O Brock. A compliant hand based on a novel pneumatic actuator. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, pages 2047–2053. IEEE, 2013.

[77] K Suzumori, S Iikura, and H Tanaka. Development of flexible microactuator and its applications to robotic mechanisms. In *Robotics and Automation, 1991. Proceedings., 1991 IEEE International Conference on*, pages 1622–1627. IEEE, 1991.

[78] K Suzumori, T Maeda, H Wantabe, and T Hisada. Fiberless flexible microactuator designed by finite-element method. *Mechatronics, IEEE/ASME Transactions on*, 2(4):281–286, 1997.

[79] F Cosentino, E Tumino, GR Passoni, E Morandi, and A Capria. Functional evaluation of the endotics system, a new disposable self-propelled robotic colonoscope: in vitro tests and clinical trial. *The International journal of artificial organs*, 32(8):517–527, 2009.

[80] JR Amend, EM Brown, N Rodenberg, HM Jaeger, and H Lipson. A positive pressure universal gripper based on the jamming of granular material. *Robotics, IEEE Transactions on*, 28(2):341–350, 2012.

[81] NineSigma web page. `http://ninesigma.com/`. Accessed: 2015-02-06.

[82] Foam - peltier effect 1. `https://www.youtube.com/watch?v=LuqtlTBVJT0`. Accessed: 2015-02-06.

[83] Foam - peltier effect 2. `https://www.youtube.com/watch?v=mi8T3f0rzn4&feature=plcp`. Accessed: 2015-02-06.

[84] Cardboard - peltier effect. `https://www.youtube.com/watch?v=ZFsGCmpeeWM&feature=plcp`. Accessed: 2015-02-06.

[85] Fiberglass - peltier effect. `https://www.youtube.com/watch?v=Fh4O6hQeDMc&feature=plcp`. Accessed: 2015-02-06.

[86] Fiberglass - electrostatic. `http://youtu.be/QwZ0RLFinuQ`. Accessed: 2015-02-06.

[87] Polystyrene - electrostatic 1. `http://youtu.be/rmHJo9XaMYo`. Accessed: 2015-02-06.

[88] Fiberglass - electrostatic 2. `http://youtu.be/T8GxUNezFDY`. Accessed: 2015-02-06.

[89] Plastic disk - micro-suction cups. `http://youtu.be/-XK8H3lxQC0`. Accessed: 2015-02-06.

[90] Cardboard - micro-suction cups. `https://www.youtube.com/watch?v=7Ao2ToQFUTE`. Accessed: 2015-02-06.

[91] Rubber - micro-suction cups. https://www.youtube.com/watch?v=2yCKwupS_Xc&feature=plcp. Accessed: 2015-02-06.

[92] Cardboard - chemical adhesive. https://www.youtube.com/watch?v=ohOQPFPEdsM. Accessed: 2015-02-06.

[93] Metal sheet - chemical adhesive. https://www.youtube.com/watch?v=cIv4YVvjZ4o. Accessed: 2015-02-06.

[94] Fiberglass - chemical adhesive. https://www.youtube.com/watch?v=oCf-RJCsYa8. Accessed: 2015-02-06.

[95] Rubber - chemical adhesive. https://www.youtube.com/watch?v=WWjpPOSYuEE&feature=plcp. Accessed: 2015-02-06.

[96] M Rohde, G Fantoni, J Tilli, and R Mortensen Ernits. A challenge for automation in logistics: gripping systems for automatically unloading of coffee sacks. *4th International Conference on Dynamics in Logistics*, 2014.

[97] MB Binnard. *Design by composition for rapid prototyping*. Kluwer Academic Publishers, 1999.

[98] OS Es-Said, J Foyos, R Noorani, M Mendelson, R Marloth, and BA Pregger. Effect of layer orientation on mechanical properties of rapid prototyped samples. *Materials and Manufacturing Processes*, 15(1):107–122, 2000.

[99] GA Teitelbaum. *Proposed build guidelines for use in fused deposition modeling to reduce build time and material volume*. ProQuest, 2009.

[100] B Caulfield, PE McHugh, and S Lohfeld. Dependence of mechanical properties of polyamide components on build parameters in the sls process. *Journal of Materials Processing Technology*, 182(1):477–488, 2007.

[101] H Scholten and W Christoph. Use of a nylon-12 for selective laser sintering, 2001. US Patent 6,245,281.

[102] DT Pham and Stefan S Dimov. *Rapid manufacturing- The technologies and applications of rapid prototyping and rapid tooling*. Springer-Verlag London, Ltd, Godalming, United Kingdom, 2001.

[103] GN Levy, R Schindel, and JP Kruth. Rapid manufacturing and rapid tooling with layer manufacturing (lm) technologies, state of the art and future perspectives. *CIRP Annals-Manufacturing Technology*, 52(2):589–609, 2003.

[104] W Griehl and D Ruestem. Nylon-12-preparation, properties, and applications. *Industrial & Engineering Chemistry*, 62(3):16–22, 1970.

[105] TJ Gornet, KR Davis, TL Starr, and KM Mulloy. Characterization of selective laser sintering materials to determine process stability. In *Proceedings of the 13 th International Solid freeform fabrication symposium*, pages 546–553, 2002.

[106] H Zarringhalam, N Hopkinson, NF Kamperman, and JJ De Vlieger. Effects of processing on microstructure and properties of sls nylon 12. *Materials Science and Engineering: A*, 435:172–180, 2006.

[107] E Moeskops, N Kamperman, B van de Vorst, and R Knopppers. Creep behaviour of polyamide in selective laser sintering. *Proceedings of SFF, Austin USA*, 2004.

[108] S Dadbin, M Frounchi, and D Goudarzi. Electron beam induced crosslinking of nylon 6 with and without the presence of tac. *Polymer Degradation and stability*, 89(3):436–441, 2005.

[109] B Bolto, T Tran, M Hoang, and Z Xie. Crosslinked poly (vinyl alcohol) membranes. *Progress in Polymer Science*, 34(9):969–981, 2009.

[110] A Gebhardt. *Rapid prototyping*. Hanser Publishers, Munich, 2003.

[111] G Eggers, J Klein, J Blank, and S Hassfeld. Piezosurgery®: an ultrasound device for cutting bone and its use and limitations in maxillofacial surgery. *British Journal of oral and maxillofacial surgery*, 42(5):451–453, 2004.

[112] DA Stephenson and JS Agapiou. *Metal cutting theory and practice*, volume 68. CRC press, 2005.

[113] JR Underwood, JR Auld, and JC Huculak. Vitrectomy probe with adjustable cutter port size, August 26 2011. US Patent App. 13/218,923.

[114] PR Ouyang, RC Tjiptoprodjo, WJ Zhang, and GS Yang. Micro-motion devices technology: The state of arts review. *The International Journal of Advanced Manufacturing Technology*, 38(5-6):463–478, 2008.

[115] T Moriwaki, E Shamoto, and K Inoue. Ultraprecision ductile cutting of glass by applying ultrasonic vibration. *CIRP Annals-Manufacturing Technology*, 41(1):141–144, 1992.

[116] VL Lanin. Ultrasonic soldering in electronics. *Ultrasonics sonochemistry*, 8(4):379–385, 2001.

[117] GF Benedict. *Nontraditional manufacturing processes*, volume 19. CRC Press, 1987.

[118] Z Yang, S Matsumoto, H Goto, M Matsumoto, and R Maeda. Ultrasonic micromixer for microfluidic systems. *Sensors and Actuators A: Physical*, 93(3):266–272, 2001.

[119] EGL Springall. Apparatus for applying adhesive, November 22 1994. US Patent 5,366,309.

[120] PS Medis and HT Henderson. Micromachining using ultrasonic impact grinding. *Journal of micromechanics and microengineering*, 15(8):1556, 2005.

[121] C Marty. *Usinages par procédés non conventionnels*. Masson, 1971.

[122] DL Duval, T Van Hauwermeiren, S Gaaloul, LR Deketele, and MR Mcdonald. Enhanced ultrasonic cleaning devices, February 28 2006. US Patent 7,004,182.

[123] A Moussatov, C Granger, and B Dubus. Cone-like bubble formation in ultrasonic cavitation field. *Ultrasonics sonochemistry*, 10(4):191–195, 2003.

[124] W Lee and J Park. Augmented foam: touchable and graspable augmented reality for product design simulation. *Japanese Society for Science of Design*, 52(6):17–26, 2006.

[125] S Barone, A Paoli, and AV Razionale. Creation of 3d multi-body orthodontic models by using independent imaging sensors. *Sensors*, 13(2):2033–2050, 2013.

[126] S Barone, A Paoli, and AV Razionale. Computer-aided modelling of three-dimensional maxillofacial tissues through multi-modal imaging. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 227(2):89–104, 2013.

[127] WR Proffit, HW Fields Jr, and LJ Moray. Prevalence of malocclusion and orthodontic treatment need in the united states: estimates from the nhanes iii survey. *The International journal of adult orthodontics and orthognathic surgery*, 13(2):97–106, 1997.

[128] RG Silva and DS Kang. Prevalence of malocclusion among latino adolescents. *American Journal of Orthodontics and Dentofacial Orthopedics*, 119(3):313–315, 2001.

[129] V Malik, S Grover, MS Sidhu, P Yadav, and P Chaudhary. Evaluation of orthodontic treatment need and its correlation with the perception, awareness and satisfaction of personal dental appearance among dental students. *J Orofacial Research*, 3(1):5–11, 2013.

[130] J Jenny. A social perspective on need and demand for orthodontic treatment. *International dental journal*, 25(4):248–256, 1975.

[131] AW Tung and HA Kiyak. Psychological influences on the timing of orthodontic treatment. *American Journal of Orthodontics and Dentofacial Orthopedics*, 113(1):29–39, 1998.

[132] N Wahl. Orthodontics in 3 millennia. chapter 9: functional appliances to midcentury. *American journal of orthodontics and dentofacial orthopedics*, 129(6):829–833, 2006.

[133] CJ Burstone. Variable-modulus orthodontics. *American journal of orthodontics*, 80(1):1–16, 1981.

[134] M Nishimura, M Sannohe, H Nagasaka, K Igarashi, and J Sugawara. Nonextraction treatment with temporary skeletal anchorage devices to correct a class ii division 2 malocclusion with excessive gingival display. *American Journal of Orthodontics and Dentofacial Orthopedics*, 145(1):85–94, 2014.

[135] K Keski-Nisula, L Keski-Nisula, H Salo, K Voipio, and J Varrela. Dentofacial changes after orthodontic intervention with eruption guidance appliance in the early mixed dentition. *The Angle orthodontist*, 78(2):324–331, 2008.

[136] K Keski-Nisula, R Hernesniemi, M Heiskanen, L Keski-Nisula, and J Varrela. Orthodontic intervention in the early mixed dentition: A

prospective, controlled study on the effects of the eruption guidance appliance. *American Journal of Orthodontics and Dentofacial Orthopedics*, 133(2):254–260, 2008.

[137] HS Baik, SH Jee, KJ Lee, and TK Oh. Treatment effects of fränkel functional regulator iii in children with class iii malocclusions. *American journal of orthodontics and dentofacial orthopedics*, 125(3):294–301, 2004.

[138] HD Kesling. Method of making orthodontic appliances and of positioning teeth, April 19 1949. US Patent 2,467,432.

[139] EO Bergersen. Orthodontic appliance and method of using same during mixed dentition stage, February 20 1979. US Patent 4,139,944.

[140] G Janson, JEP de Souza, MR de Freitas, JF Castanha Henriques, and CT Cavalcanti. Occlusal changes of class ii malocclusion treatment between fränkel and the eruption guidance appliances. *The Angle Orthodontist*, 74(4):521–525, 2004.

[141] G Janson, A Nakamura, K Chiqueto, R Castro, MR de Freitas, and JFC Henriques. Treatment stability with the eruption guidance appliance. *American Journal of Orthodontics and Dentofacial Orthopedics*, 131(6):717–728, 2007.

[142] GE Halverson and GA Nelson. Dental impression supply kit, August 16 1988. US Patent 4,763,791.

[143] RJ Miller, E Kuo, DE Falvey, and AH Trosien. Methods for modeling bite registration, June 24 2003. US Patent 6,582,229.

[144] CH Kau, S Richmond, A Incrapera, J English, and JJ Xia. Three-dimensional surface acquisition systems for the study of facial morphology and their application to maxillofacial surgery. *The International Journal of Medical Robotics and Computer Assisted Surgery*, 3(2):97–110, 2007.

[145] MY Hajeer, DT Millett, AF Ayoub, and JP Siebert. Current products and practices applications of 3d imaging in orthodontics: part i. *Journal of orthodontics*, 31(1):62–70, 2004.

[146] MY Hajeer, DT Millett, AF Ayoub, and JP Siebert. Current products and practices applications of 3d imaging in orthodontics: Part ii. *Journal of orthodontics*, 31(2):154–162, 2004.

[147] S Barone, A Paoli, AV Razionale, and R Savignano. Computer aided modelling to simulate the biomechanical behaviour of customised orthodontic removable appliances. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, pages 1–14, 2014.

[148] DV Rosato, DV Rosato, and MG Rosato. *Injection molding handbook*. springer, 2000.

[149] M Salmi, J Tuomi, R Sirkkanen, T Ingman, and A Mäkitie. Rapid tooling method for soft customized removable oral appliances. *The open dentistry journal*, 6:85, 2012.

[150] Chee Kai Chua, Kah Fai Leong, and Chu Sing Lim. *Rapid prototyping: principles and applications*. World Scientific, 2010.

[151] LM Galantucci, F Lavecchia, and G Percoco. Experimental study aiming to enhance the surface finish of fused deposition modeled parts. *CIRP Annals-Manufacturing Technology*, 58(1):189–192, 2009.

[152] Gianluca Percoco, Fulvio Lavecchia, and Luigi Maria Galantucci. Compressive properties of fdm rapid prototypes treated with a low cost chemical finishing. *Research Journal of Applied Sciences, Engineering and Technology*, 4(19):3838–3842, 2012.

[153] G Fantoni and J Tilli. Dispositivo e metodo per lavorazione ad ultrasuoni, 2014. Italian Patent Application No. PI 2014 A000055.